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EXAMPLES OF THE MEAN THREE-DIMENSIONAL WIND CIRCULATION OVER THE TROPICAL NORTH PACIFIC OCEAN

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ABSTRACT

Two extreme climatological contrasts in the 1954 mean monthly wind circulation over the tropical North Pacific Ocean are presented in the form of cross sections and horizontal analyses. The wind field is shown on cross sections near 165° E. from 5° to 35° N. latitude. The horizontal variations of the wind are shown at 10,000-foot intervals throughout the troposphere and lower stratosphere. Twenty-seven figures are presented.

1. INTRODUCTION

Until recently, the lack of upper air data in the Tropics has prevented climatologists from preparing maps depicting mean high-level circulation patterns over most of the tropical North Pacific Ocean. In an attempt to correct the lack, as far as this is possible with recent RAWIN data, one phase of the work conducted in tropical meteorology at the Oahu Research Center has been the drawing of detailed analyses of mean monthly winds for various atmospheric levels over the Marshall Islands (Korshover [1]). Although limited data have confined Korshover's work to the atomic weapons testing periods consisting of GREENHOUSE (spring 1951), IVY (fall 1952), and CASTLE (spring 1954), study of the analyses has suggested that *two*, significantly different, mean wind flow patterns regularly occur over the Marshall Islands. Consequently, it is the purpose of this paper to describe these patterns more fully by extending the three-dimensional analysis of the mean wind flow patterns to the entire tropical North Pacific Ocean area.

2. THE TWO MEAN WIND FLOW PATTERNS

The first mean wind flow pattern illustrated (figs. 8–17) is derived from winds prevailing during the month of February 1954. This was a "high index" period and the horizontal analyses are believed to be typical at each level of the mean wind circulation over the tropical North Pacific Ocean area during high zonal index in temperate latitudes. Daily analyses show that the synoptic flow pattern in the middle and high troposphere through the month was essentially zonal and strong in speed.

The second mean wind flow pattern illustrated (figs. 18–27) is based on winds observed during the period April 16 through May 15, 1954. For this interval of time the mean horizontal analyses are believed to be typical at each level studied of the mean wind circulation during a "low index" period. That the mean wind analyses are representative of high and low index situations can be checked by the striking similarity of the climatological maps to the daily synoptic maps for the same periods as analyzed by the weather personnel on OPERATION CASTLE. In other words, the daily departure of the synoptic field of motion, from the mean, for both periods was very small.

The meager evidence from years before 1954 (almost

[1] The research work in this paper has been made possible by support of the Geophysics Research Directorate of the Air Force Cambridge Research Center under Contract No. AF19(604)-546.

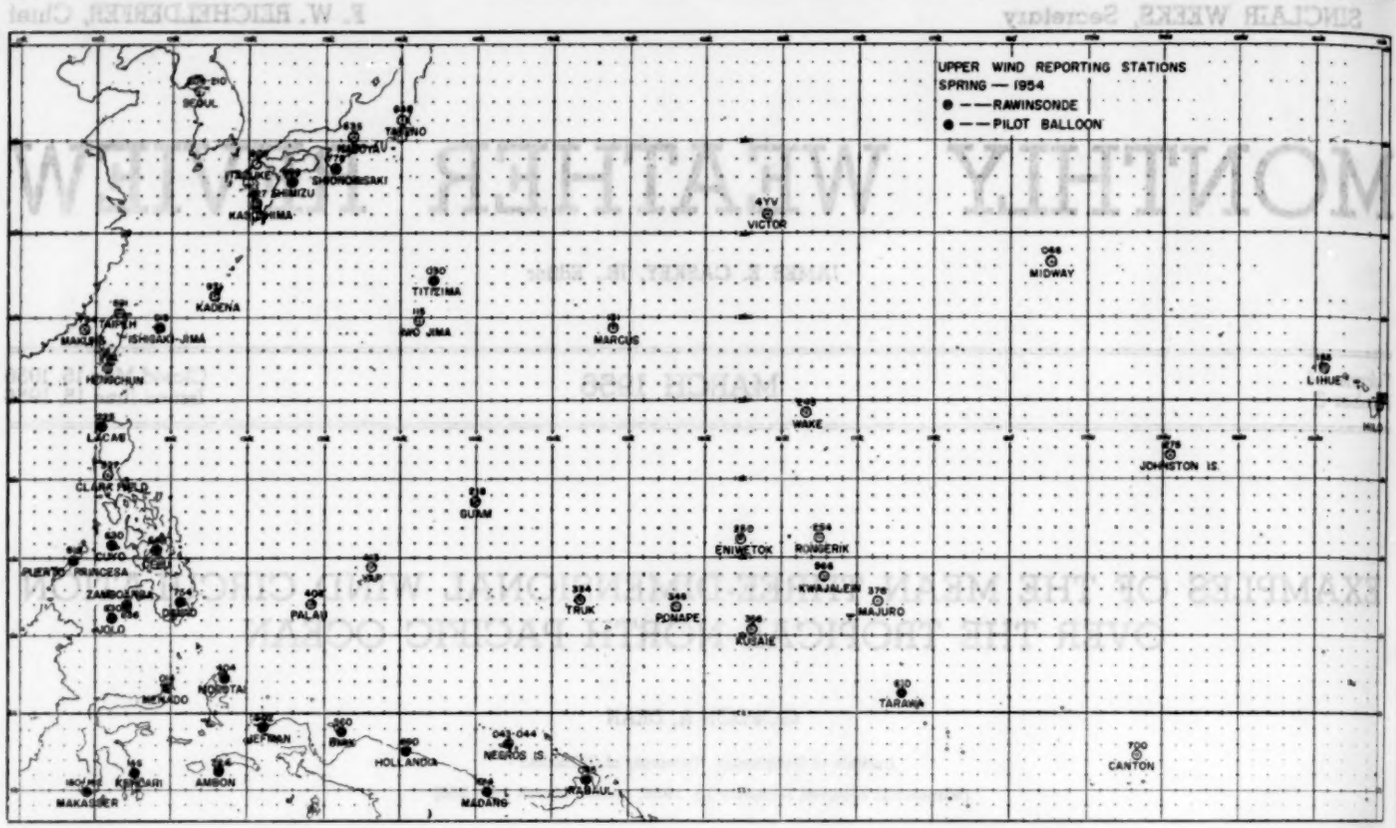

FIGURE 1.—Upper-air observing network in the Central Pacific during spring 1954.

TABLE 1.—*Pacific upper-wind stations, types of wind finding equipment, and times of observation*

Station No.	Station name	Type of wind finding equipment**	Time of observation (GMT)
	Block 91		
066	Midway	R	03, 09, 15, 21
115	Iwo Jima	R	03, 09, 15, 21
131	Marcus	R	03, 09, 15, 21
4YV	Victor	R	03, 09, 15, 21
165	Lihue	R	03, 09–P, 15, 21–P
218	Guam	R	03, 09, 15, 21
245	Wake	R	03, 09, 15, 21
250*	Eniwetok	R	03, 09, 15, 21
254	Rongerik	R	03, 09, 15, 21
275	Johnston	R	03, 09, 15, 21
285	Hilo	R	03, 09–P, 15, 21–P
334	Truk	R	03, 15–P
348*	Ponape	R	03, 09, 15, 21
356*	Kusaie	R	03, 09, 15, 21
366*	Kwajalein	R	03, 09, 15, 21
376*	Majuro	R	03, 09, 15, 21
408	Palau	R	03, 15–P
413	Yap	R	03, 15–P
530	Nauru	CL	00, 06
533	Ocean	CL	00, 06, 12, 18
610	Tarawa	P	05, 11, 17, 23
623	Beru	CL	00, 06, 18
487	Fanning	CL	00, 06, 18
490	Christmas	CL	00, 06, 18
700	Canton	R	03, 09, 15, 21
705	Gardner	CL	00, 06, 18
10	Hull	CL	00, 06, 18
	Block 46		
697	Taipeh	R	03, 09, 15, 21
734	Makung	R	03, 09, 15, 21
752	Hengchun	R	03, 09, 15, 21
	Block 47		
208	Seoul	R	03, 09, 15, 21
635	Nagoya	R	03, 09, 15, 21
646	Tateno	R	03, 15
778	Shionomisaki	R	03, 09, 15, 21
808	Itazuke	R	03, 09, 15, 21
827	Kagoshima	R	03, 09, 15, 21
898	Shimizu	P	03, 09, 15, 21
931	Okinawa	R	03, 09, 15, 21
	Block 94		
014	Madang	P	04, 10, 16, 22
085	Rabaul	P	04, 10, 16, 22
	Block 97		
014	Menado	P	05, 11, 23
146	Kendari	P	05, 11, 23
180	Makasser	P	05, 11, 23
404	Moritai	P	05, 11, 23
502	Jefman	P	02, 08, 23
560	Biak	P	03, 08, 22
690	Hollandia	P	02, 08, 22
724	Ambon	P	05, 11, 23
	Block 98		
223	Laoag	P	03, 15
327	Clark Field	R	03, 09, 15, 21
618	Puerto Princesa	P	03, 15, 21
630	Cuyo	P	03, 21
645	Cebu	P	03, 15
754	Davao	P	03, 15
830	Jolo	P	03, 09
836	Zamboanga	P	03, 15, 21

*Occasionally 3-hourly observations are included in addition to the required 6-hourly observations.
**R=Rawinsonde. P=Pilot balloon. CL=Low-level cloud direction.

TABLE 2.—*Number of wind observations at each wind analysis level*

Station	Level (ft.)									
	2,000	10,000	20,000	30,000	40,000	50,000	60,000	65,000	70,000	80,000
FEBRUARY 1-28, 1954										
Block 91										
4YV	80	79	50	17						
066	108	110	106	88	64	41	24	20	17	11
115	90	69	53	41	28	18	10	9	10	9
131	106	106	107	91	71	38	18	8		
165	97	74	64	47	34	23	10	10		
218	111	111	108	106	105	89	49	45	39	26
245	108	110	107	98	79	44	17	13		
250	123	123	122	123	123	122	94	92	86	64
254	82	87	85	85	85	79	56	51	51	42
275	112	110	109	108	100	89	58	49	45	37
285	90	70	61	48	37	27				
334	54	47	30	27	26	22	16	15	16	
348	106	106	108	108	108	107	71	69	69	63
356	101	108	107	109	109	107	75	66	63	57
366	117	108	81	71	66	58	48	41	38	29
376	107	109	110	108	107	104	93	91	89	85
408	52	42	23	10	7					
413	47	41	32	26	26	22	14	15	11	
610	102	23								
700	112	105	77	63	62	49	26	21	13	
Block 46										
697	59	53	47	38	22					
734	73	65	59	37						
752	73	71	64	61	62	41				
Block 47										
208	69	71	64	56	41	29				
635	101	82	61	49	29	21				
646	47	48	48	44	34	19				
778	100	90	72	40						
808	94	60	51	42	26					
827	91	64	57	19						
898	89	62	22							
931	86	55	39	24						
Block 94										
014	43	31								
044	12									
085	38									
Block 97										
014	38									
146	44	23								
180	44	19								
404	21									
502	20									
560	44									
590	27									
724	55	34								
Block 98										
223	41	40	24	16						
327	88	76	60	51	48	38				
618	33	26								
630	36	30								
645	47	34								
754	47	34	23	17						
830	47	33								
836	43	39	22							

Station	Level (ft.)									
	2,000	10,000	20,000	30,000	40,000	50,000	60,000	65,000	70,000	80,000
APRIL 16-MAY 15, 1954										
Block 91										
4YV	103	95	84	64	46	32	21			
066	118	111	106	102	85	50	27	22	17	
115	94	104	104	104	104	96	62	57	50	40
131	115	114	111	103	99	86	65	59	50	35
165	115	78	67	63	60	33	19	17	15	
218	114	114	114	110	105	98	63	58	53	35
245	115	117	116	116	111	95	66	51	43	16
250	146	144	142	140	140	137	109	99	91	81
275	117	117	117	117	114	72	39	30	27	26
285	110	83	71	60	53	36	24			
334	57	54	32	22	20	18	13	14	12	
348	130	130	130	130	129	129	108	97	94	89
356	126	129	128	129	129	113	84	76	74	72
366	139	130	130	137	136	109	58	51	48	34
376	125	128	128	127	126	121	86	88	86	77
408	58	50	41	30	26	23	19	18		
413	57	43	30	25	24	21				
610	73	32								
700	120	114	97	83	73	58	33	24	19	
Block 46										
697	49									
752	79	78	76	78	75	67				
Block 47										
208	89	87	89	81	56	25				
635	102	90	72	53	43					
646	55	56	54	52	41	26				
778	99	83	58	46	24					
808	106	101	95	67	46	23				
827	92	75	55	27						
898	80	55								
931	108	107	104	98	95	64				
Block 94										
014	39	23								
085	46	25								
Block 97										
014	42	26								
146	24	18								
180	53	34								
404	26	22								
502	42	29								
560	37	20								
590	65	21								
724	37	21								
Block 98										
223	49	46	31	18						
327	114	105	83	62	50	37				
618	25	18								
630	47	30								
645	48	42	33							
754	43	31	19							
830	18	14								
836	41	39	29							

entirely confined to periods during which tests were made in the Marshalls) strongly suggests that, if a long series of observations were available, the two situations presented here as "high" and "low" index would be typical in the tropical Pacific of the months February and May; that is, that anticyclogenesis aloft in the Central Pacific culminates in February, cyclogenesis in May. However, the voluminous data upon which a firm statement about seasonal trends could be made have yet to be collected. For this reason, the terms "high" and "low" index, as used here, are purely qualitative and descriptive, and no attempt is made to disentangle the synoptic from the seasonal aspects of the two situations. In the high-index situation, the jet stream is strong in speed, the subtropical anticyclones aloft lie close to the equator, and the entire flow pattern is strongly zonal. In the low-index situation the jet stream is weak, the subtropical anticyclones aloft are centered outside

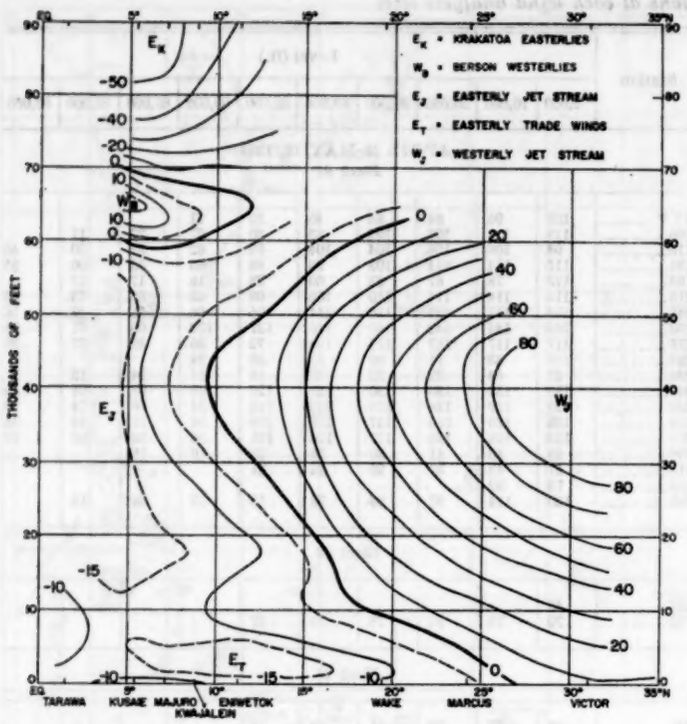

FIGURE 2.—Mean zonal component of the wind in knots near 167° E., February 1954.

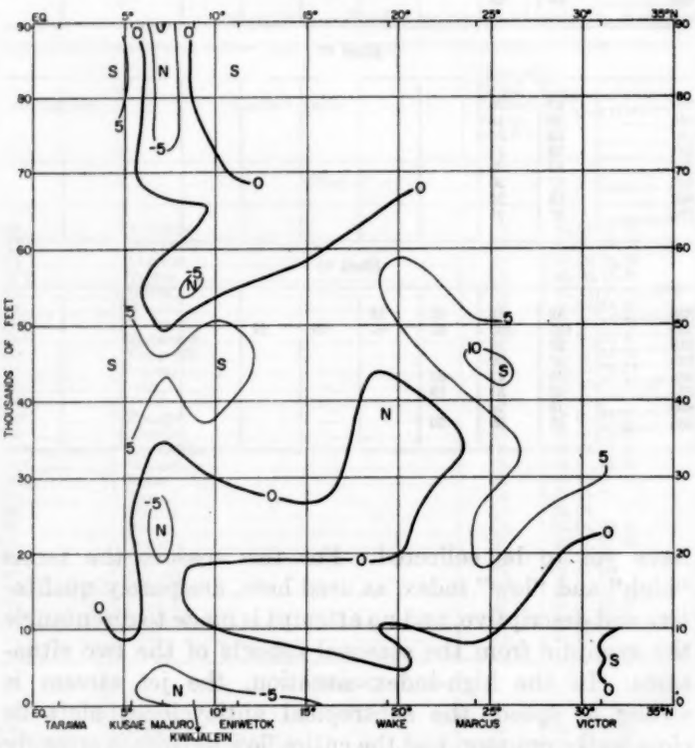

FIGURE 3.—Mean meridional component of the wind in knots near 167° E., February 1954.

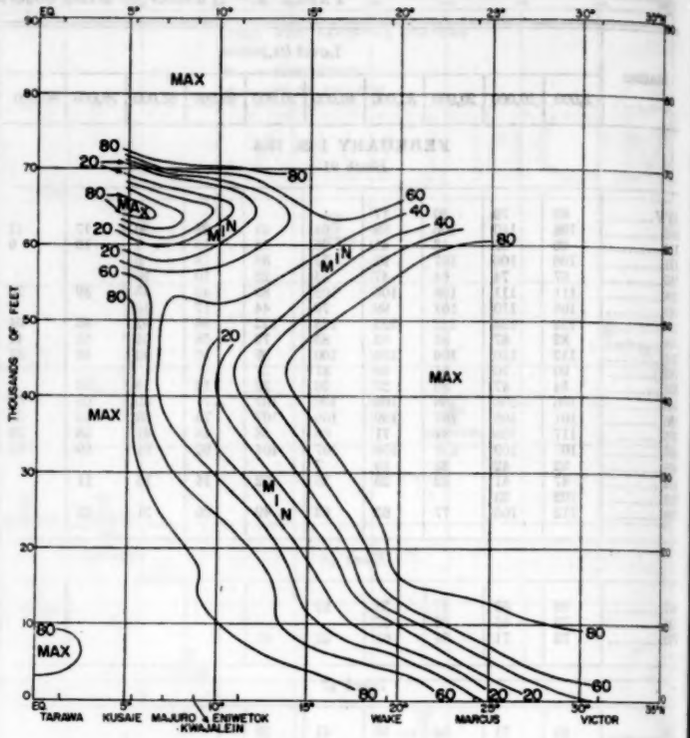

FIGURE 4.—Steadiness of the wind in percent near 167° E., February 1954.

the Tropics, and the wind pattern aloft shows large meridional air movement associated with upper-level cyclogenesis. The maps presented here illustrate the low-latitude concomitants of these situations. The difficult question of the part played by seasonal variation has to be treated at greater length in future publications.

3. ANALYSIS METHOD

The area of analysis extended from Hawaii to the coast of Asia in the east-west direction and from 0° to 35° N. in the north-south direction. The lowest level of analysis selected was 2,000 feet; winds at that level are not affected by possible orographic disturbances due to low-lying atolls. Good evidence of profound orographic effects is seen near the borders of the maps, such as in the Philippines, Formosa, and Japan. Here, the 2,000- and even 10,000-foot winds reveal large departures from a consistently smooth flow.

Above 2,000 feet, and starting with the 10,000-foot chart, the wind analyses have been carried out at 10,000-foot intervals to 80,000 feet (figs. 8–27). Because the wind structure immediately above the tropopause is complex, an additional chart at 65,000 feet has been included.

All upper wind data were obtained from teletypewriter collectives received at various stations in the Pacific. The upper wind reporting stations, their type of wind-finding equipment, and their scheduled times of observa-

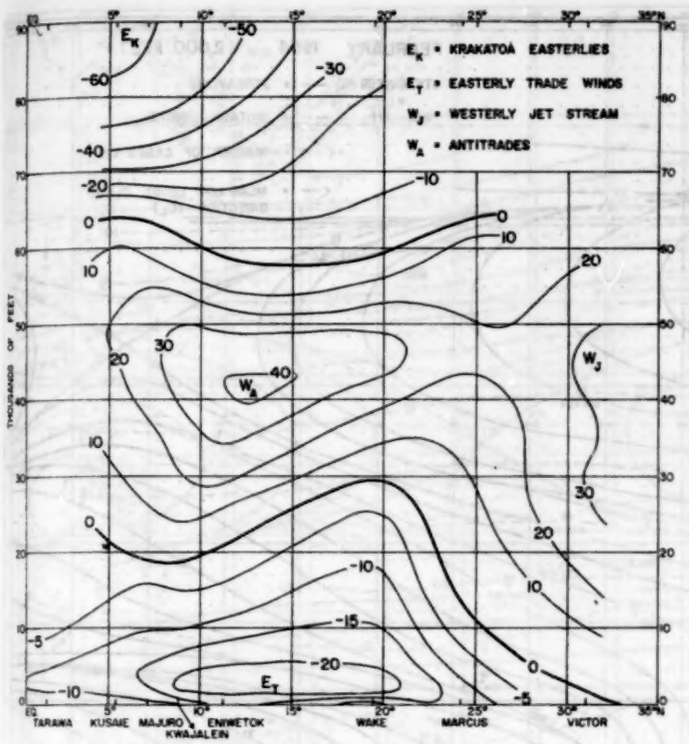
E_K • KRAKATOA EASTERLIES
E_T • EASTERLY TRADE WINDS
W_J • WESTERLY JET STREAM
W_A • ANTITRADES
THOUSANDS OF FEET
EQ TARAWA 5° KUSAIE 10° MAJURO KWAJALEIN ENIWETOK 15° WAKE 20° MARCUS 25° 30° VICTOR 35°N

FIGURE 5.—Mean zonal component of the wind in knots near 167° E., April 16–May 15, 1954.

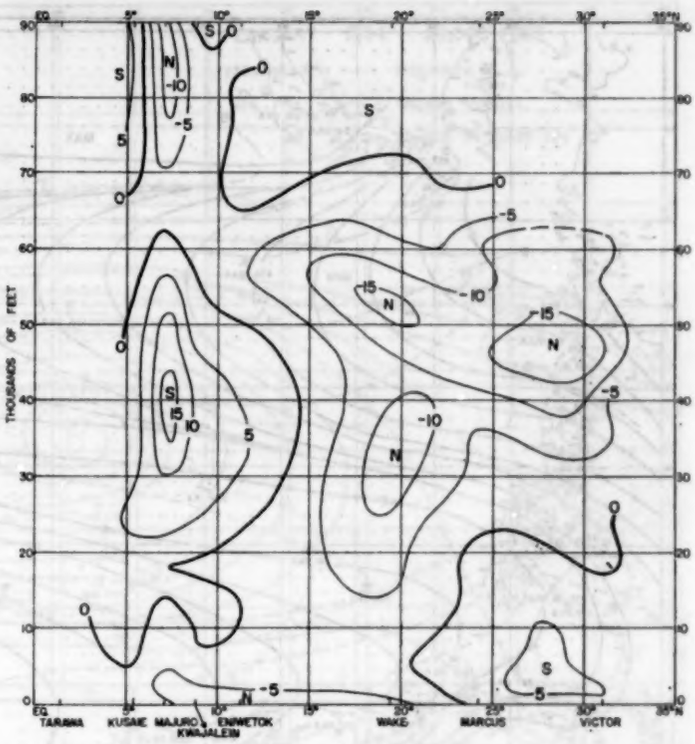

FIGURE 6.—Mean meridional component of the wind in knots near 167° E., April 16–May 15, 1954.

tion are listed in table 1 for reference. The geographic distribution of the stations is shown in figure 1. Table 2 contains the number of wind observations that were used to arrive at the mean resultant wind value for each analysis level.

The streamline analyses have been performed by the isogon method (Palmer and others [2]). The speed lines have been drawn for 10-knot intervals, and occasionally where gradients were weak, a 5-knot interval was used.

The three-dimensional aspect of the wind circulation shown on each horizontal wind chart may be enhanced through the use of a wind cross-section drawn for 167° E. The $\bar{u}$ and $\bar{v}$ components of the wind and the wind steadiness ($\overline{S}=\frac{|\overline{\mathbf{V}}|}{\overline{C}}$ where S is the steadiness, $|\overline{\mathbf{V}}|$ is the mean vector speed, and $\overline{C}$ is the mean wind speed irrespective of wind direction) are presented in figures 2–7. The names of all large-scale wind systems have been identified at their centers with appropriate symbols (Palmer [2], [3]).

4. COMMENTS ON THE MAPS

The following points deserve special emphasis:

1. No other tropical region in the world contains so dense a RAWIN observational network as that now in existence in the Central Pacific.

2. The wind circulations presented herein were selected

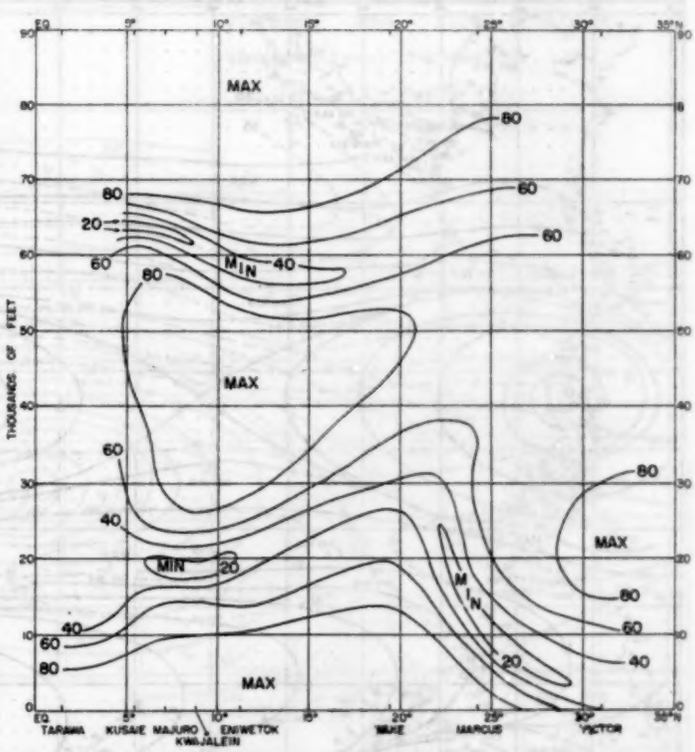

FIGURE 7.—Steadiness of the wind in percent near 167° E., April 16–May 15, 1954.

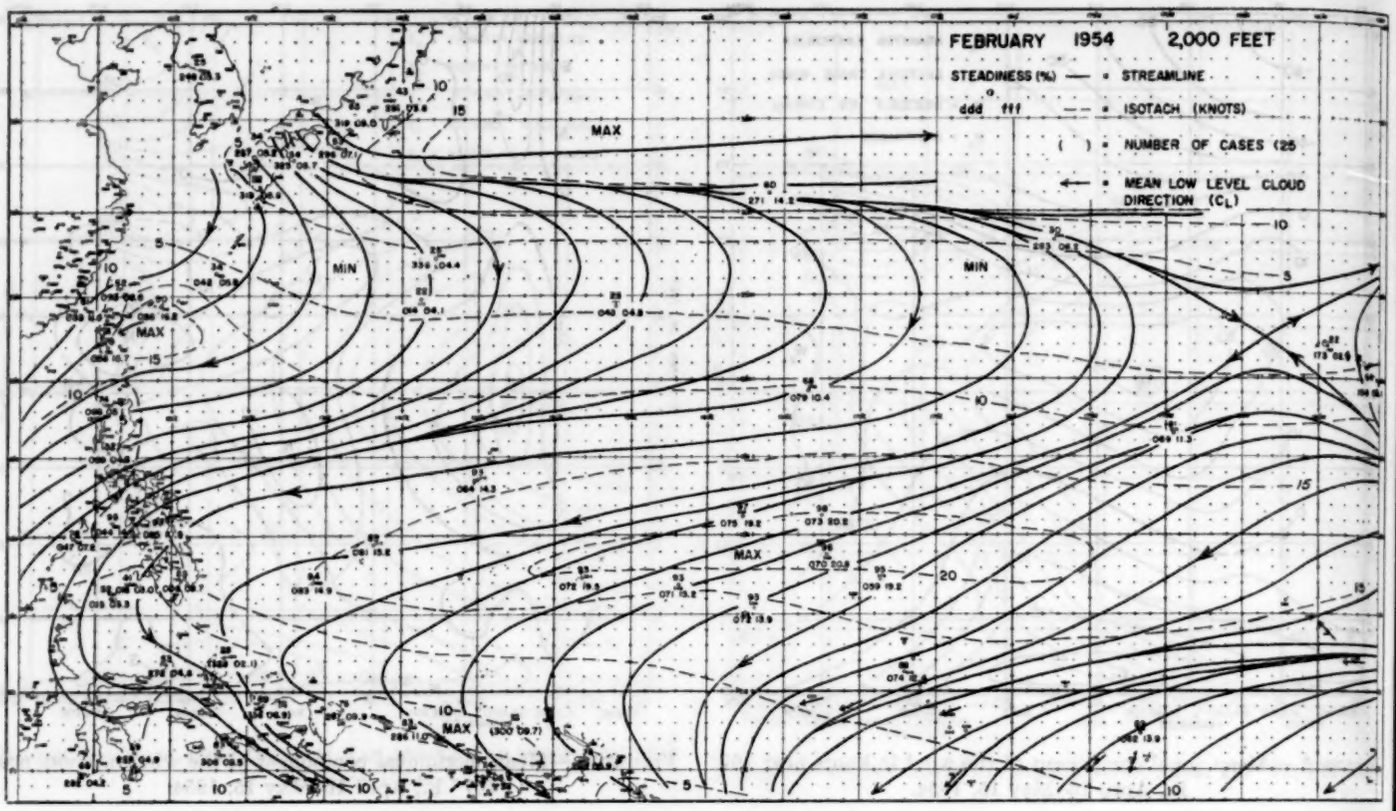
FEBRUARY 1954 2,000 FEET
STEADINESS (%) —— = STREAMLINE
ddd fff — — = ISOTACH (KNOTS)
( ) = NUMBER OF CASES (25
←— = MEAN LOW LEVEL CLOUD DIRECTION (C_L)
MAX
MIN

FIGURE 8.—The field of motion at 2,000 feet, February 1954.

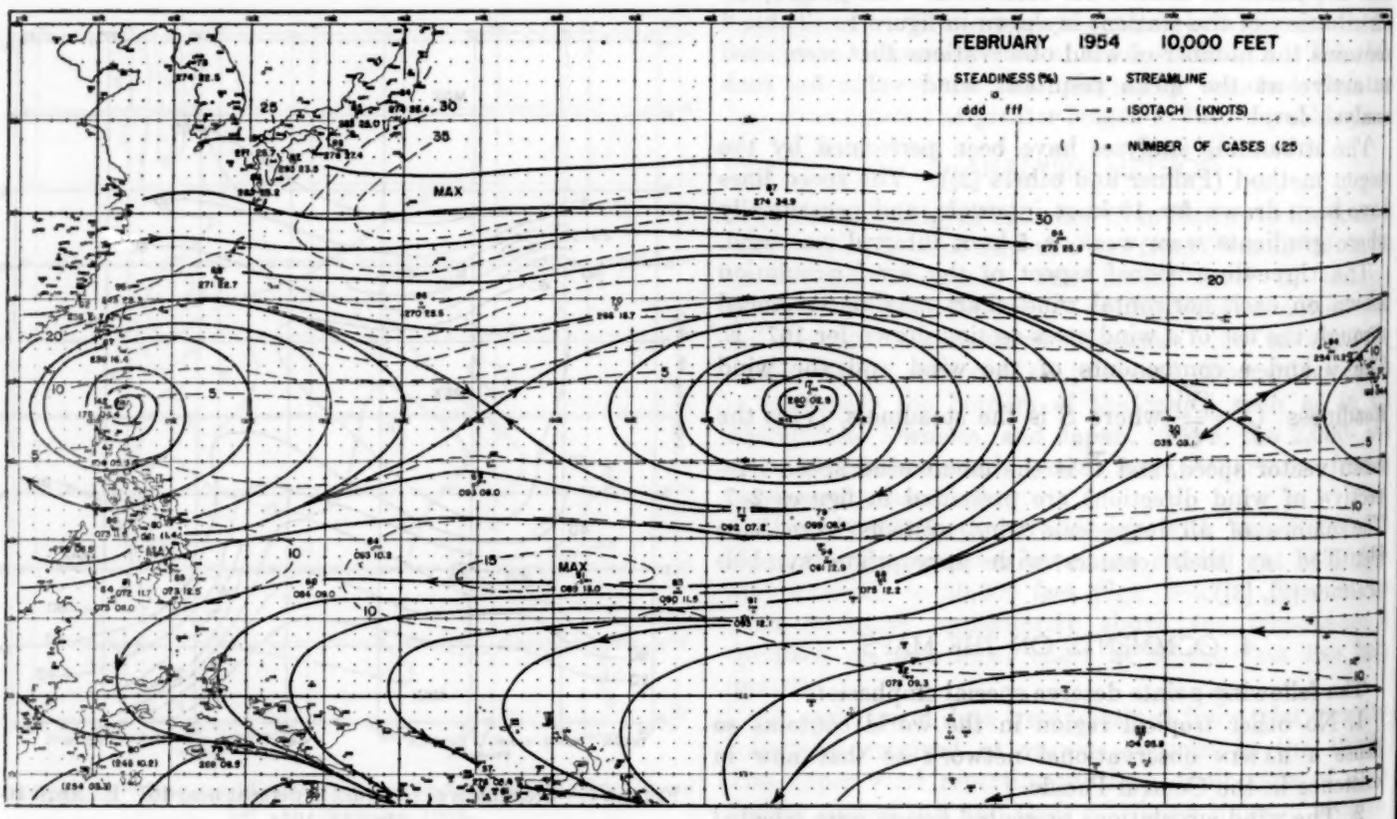

FIGURE 9.—The field of motion at 10,000 feet, February 1954.

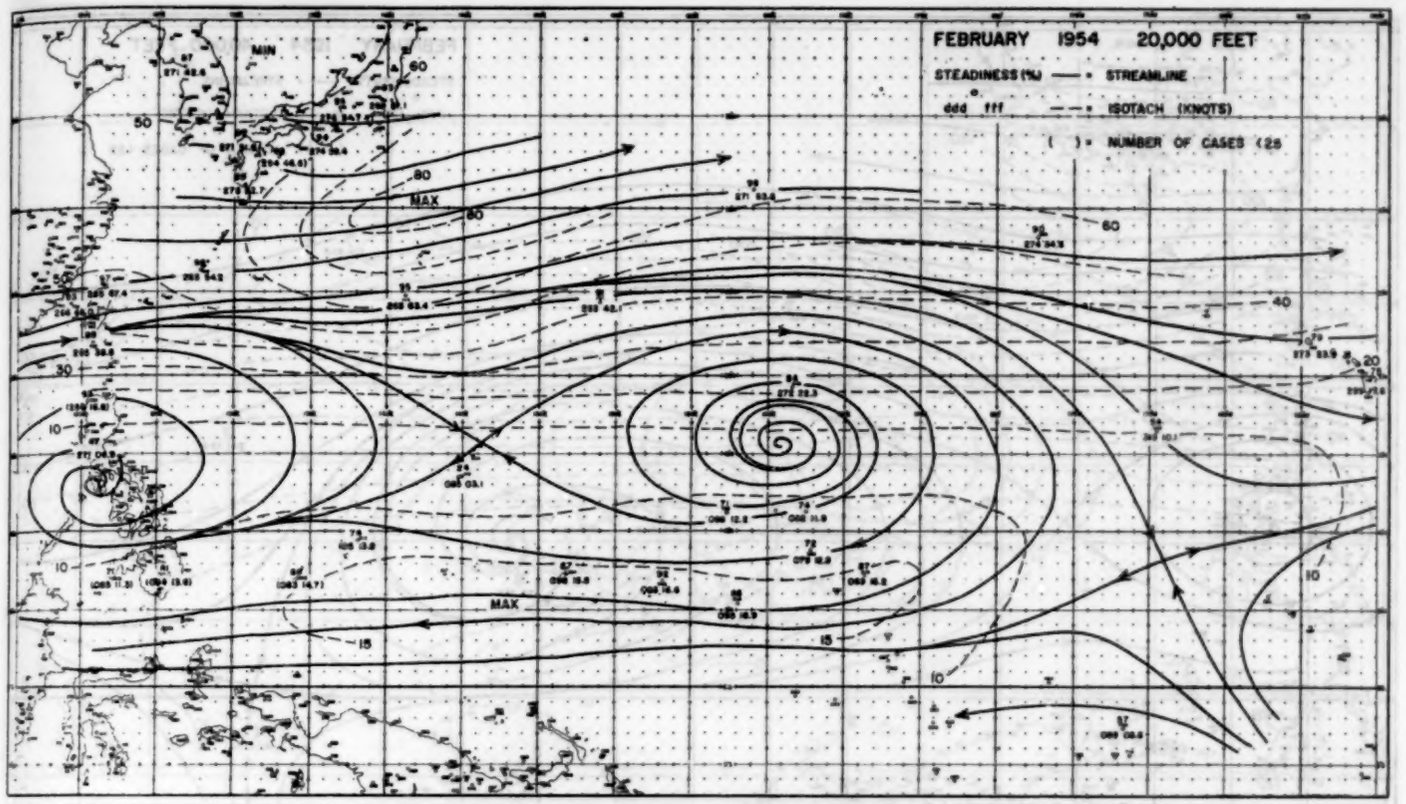

FIGURE 10.—The field of motion at 20,000 feet, February 1954.

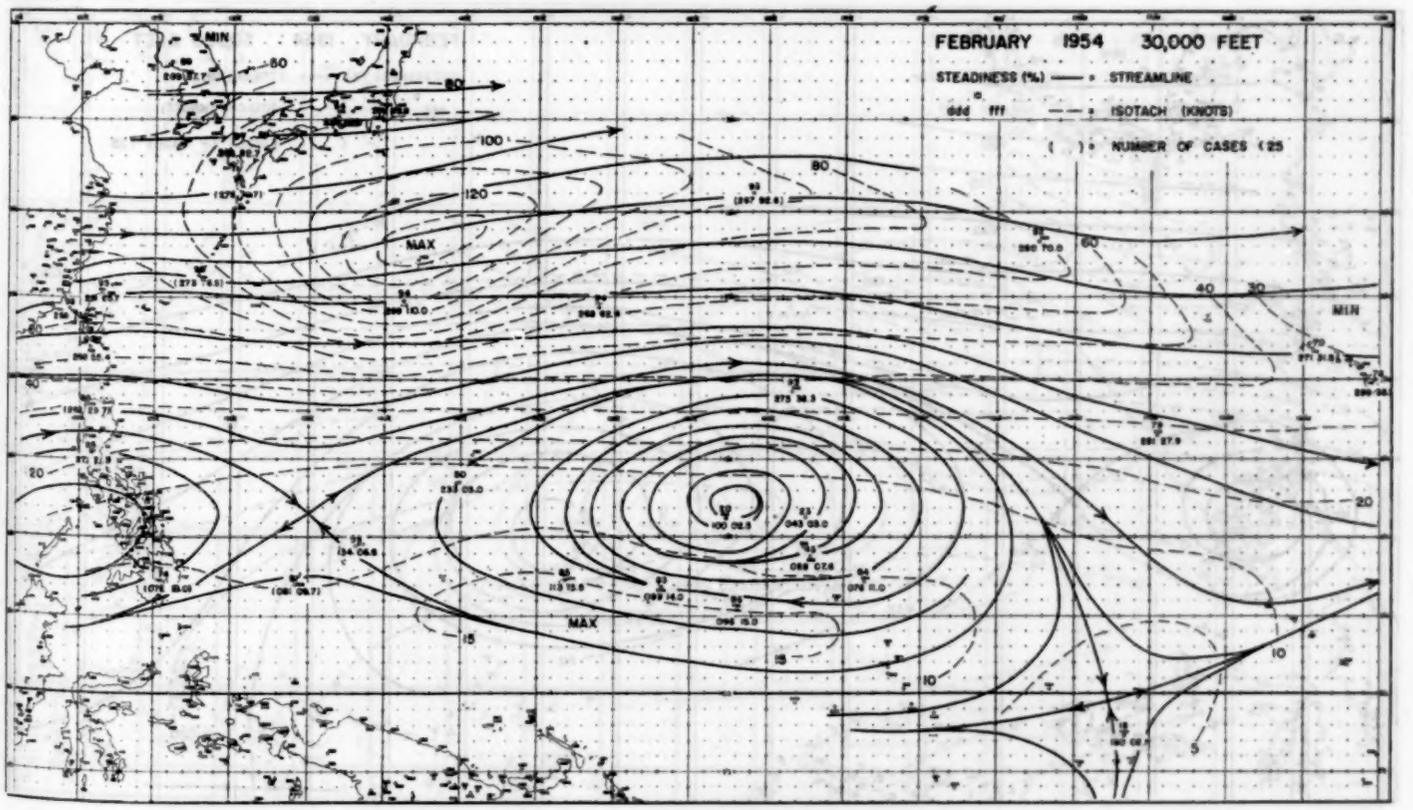

FIGURE 11.—The field of motion at 30,000 feet, February 1954.

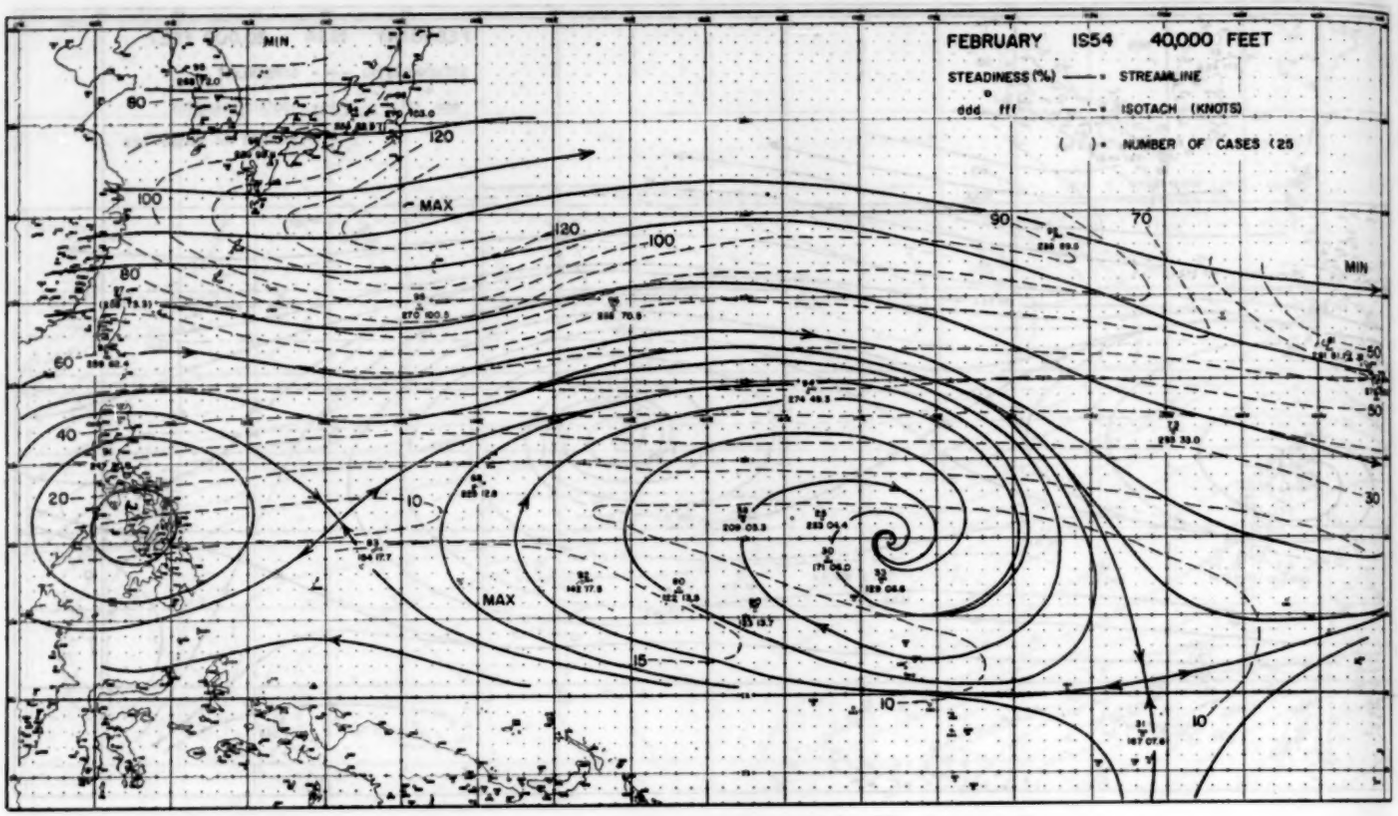

FIGURE 12.—The field of motion at 40,000 feet, February 1954.

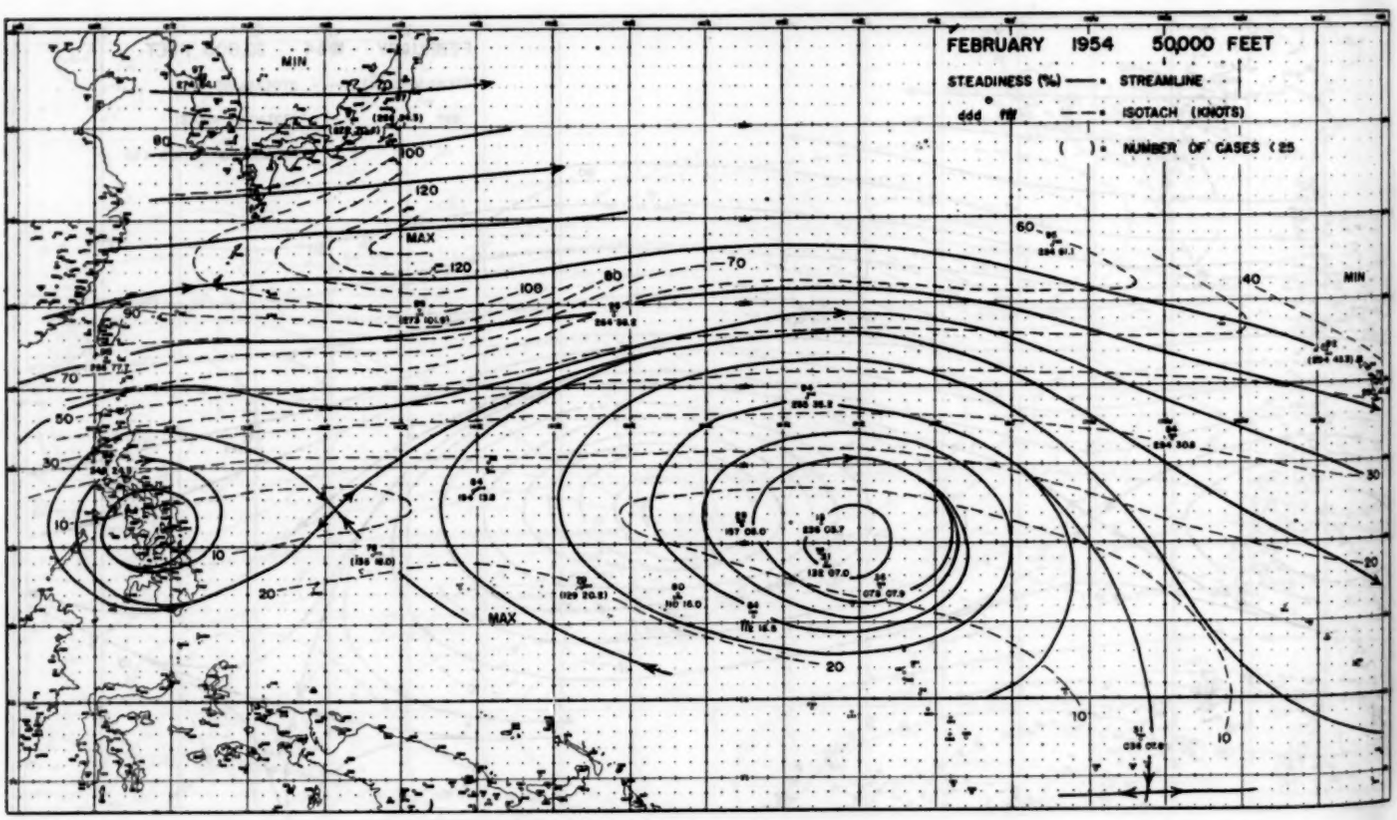

FIGURE 13.—The field of motion at 50,000 feet, February 1954.

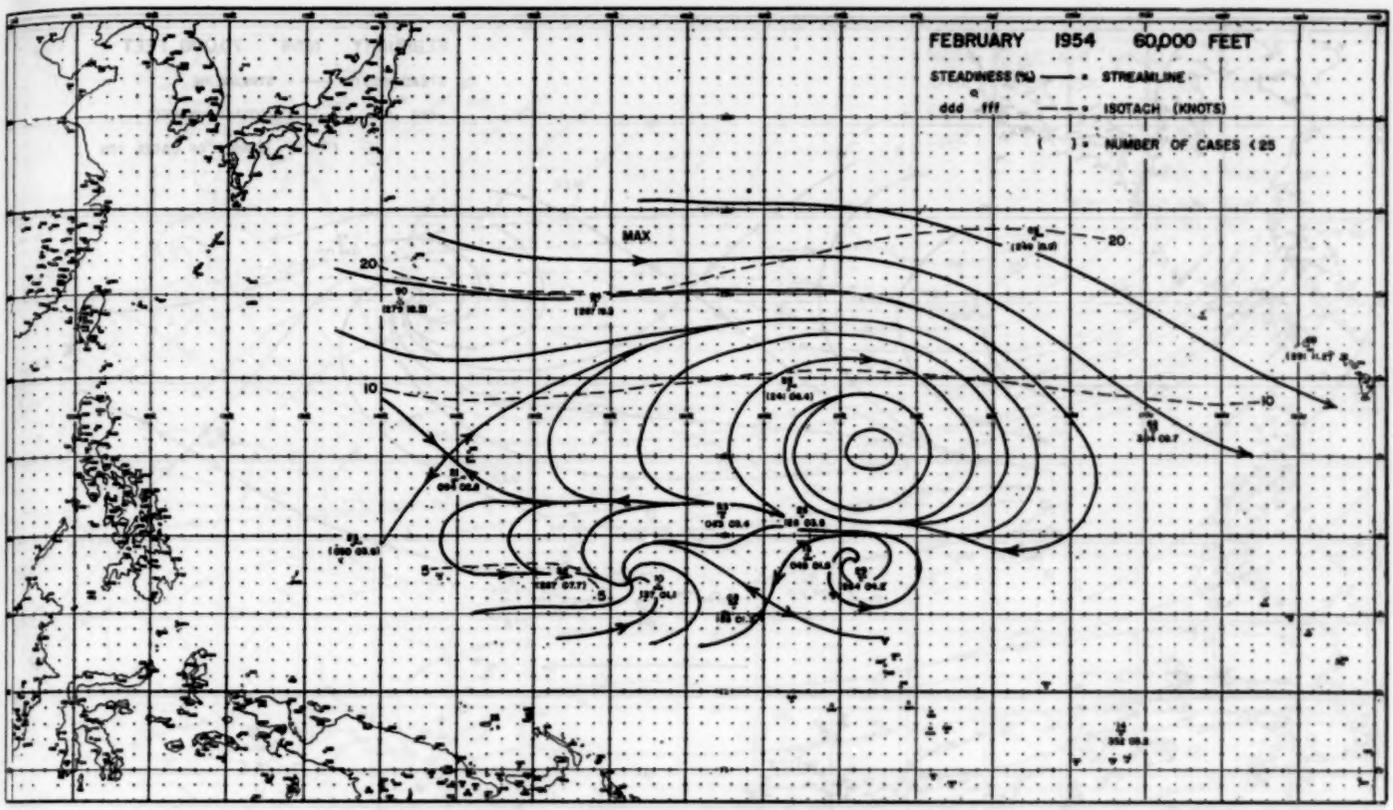

FIGURE 14.—The field of motion at 60,000 feet, February 1954.

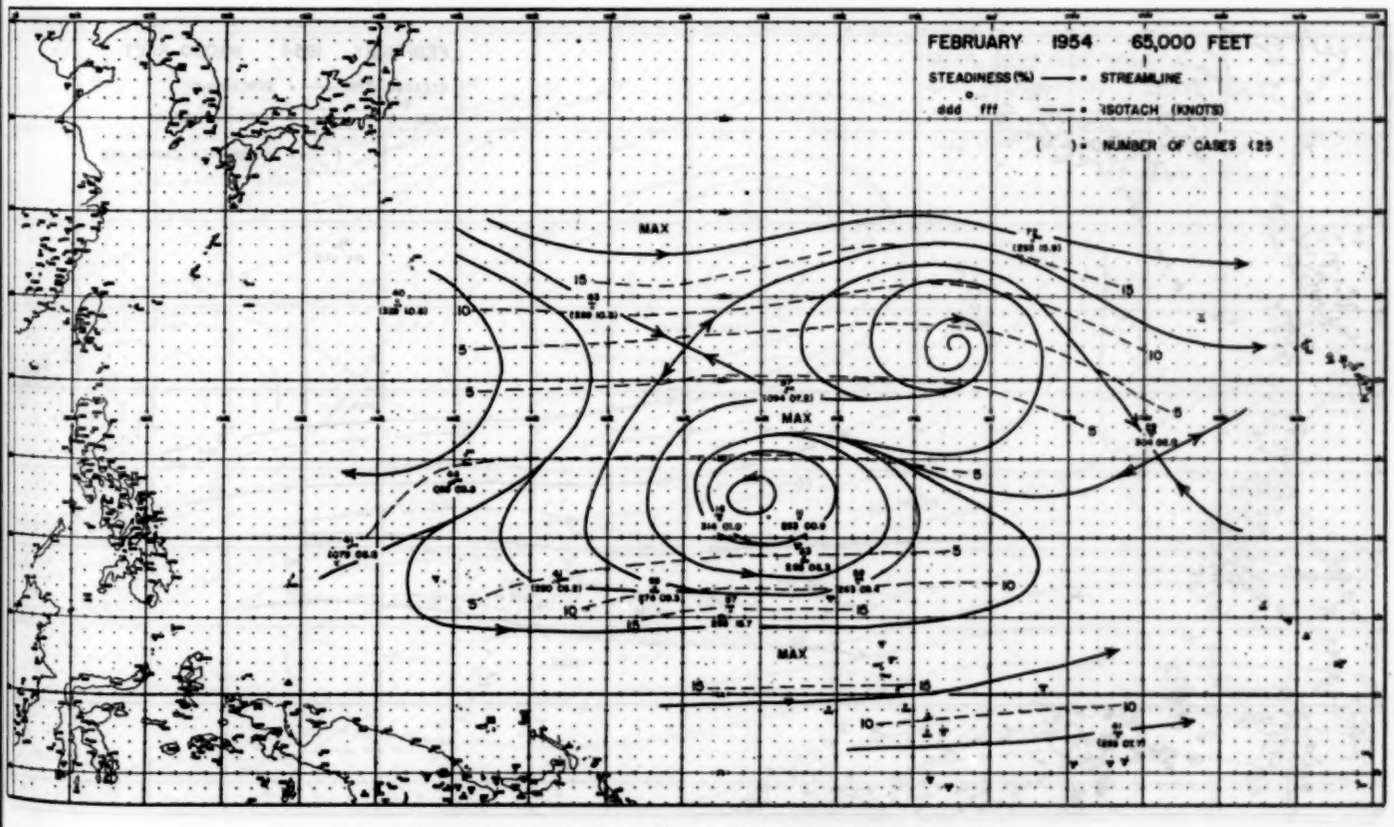

FIGURE 15.—The field of motion at 65,000 feet, February 1954.

383291—56——2

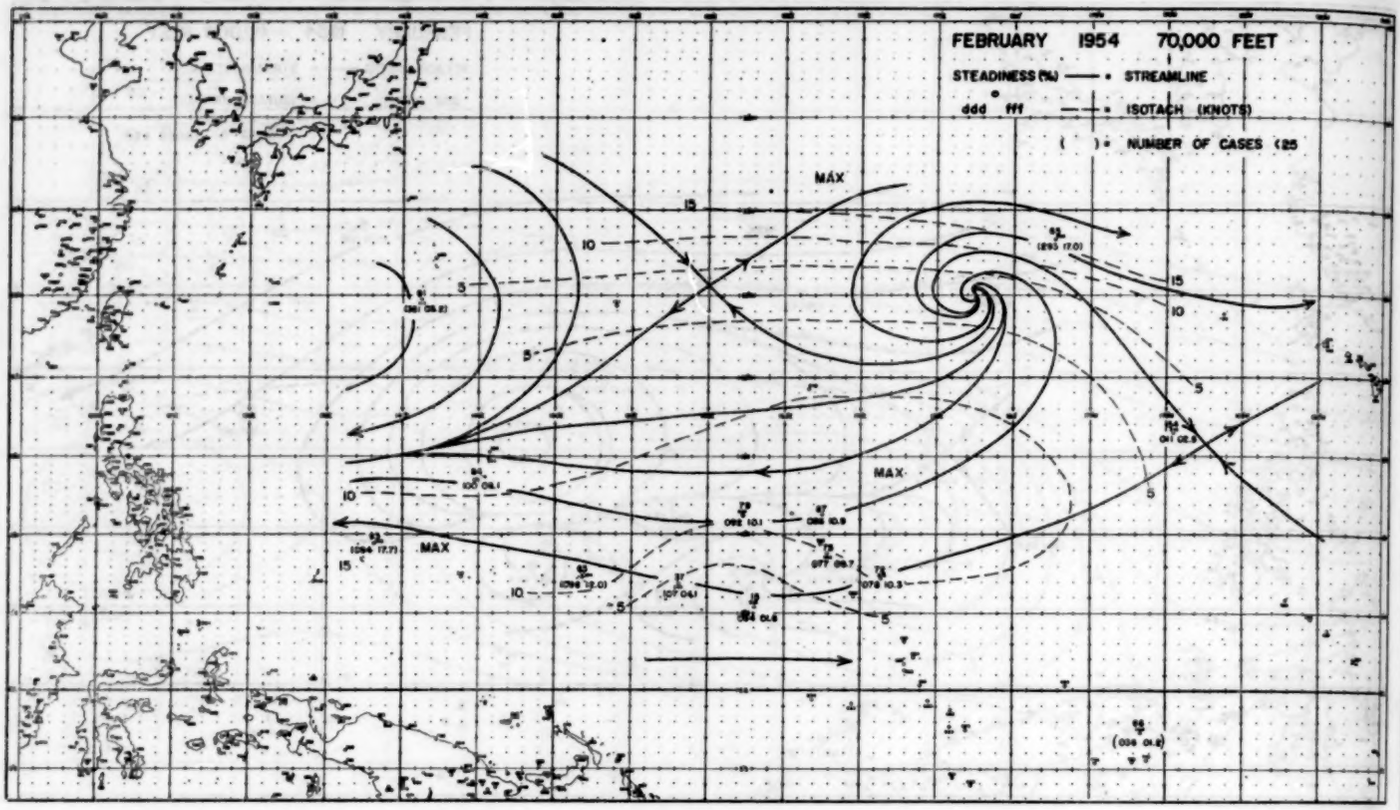

FIGURE 16.—The field of motion at 70,000 feet, February 1954.

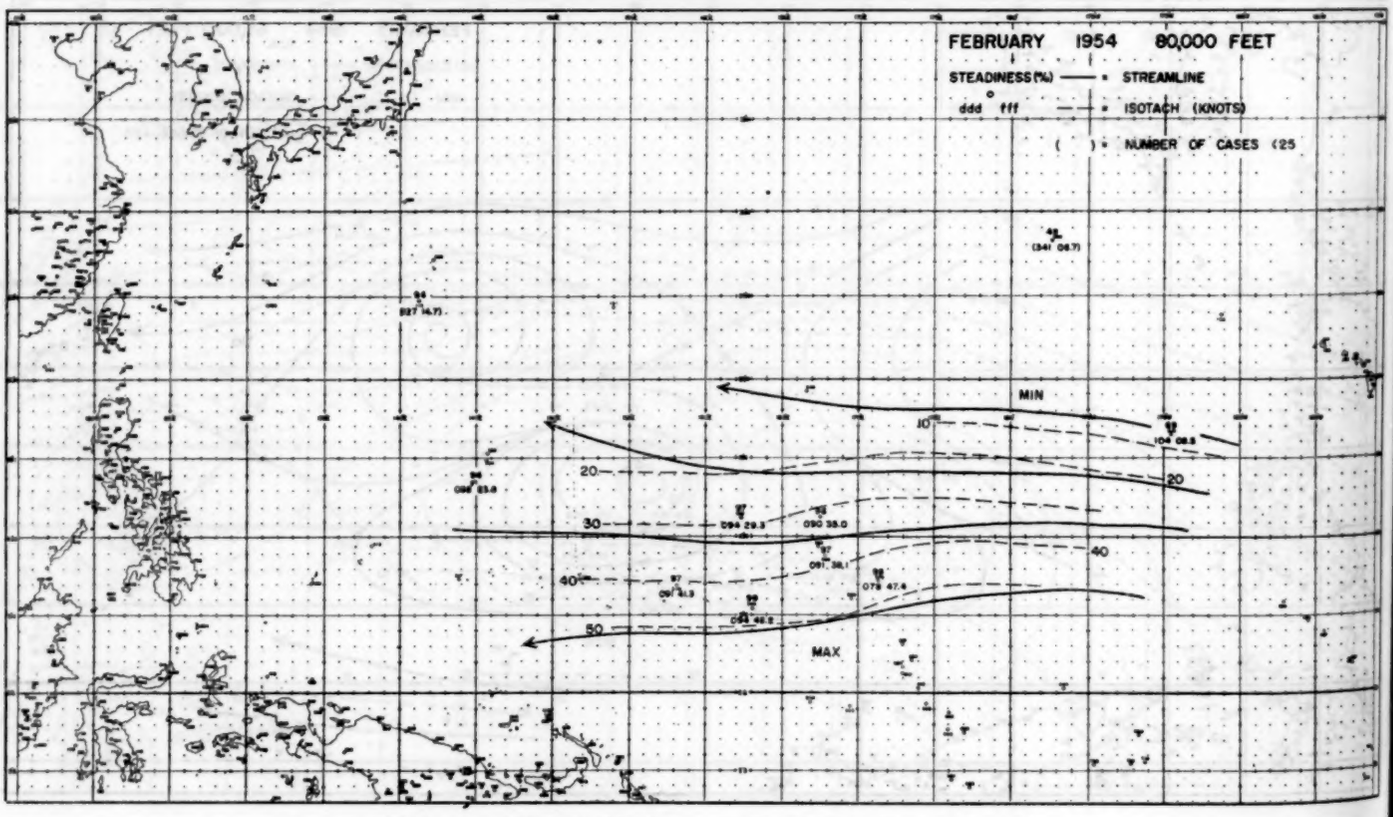

FIGURE 17.—The field of motion at 80,000 feet, February 1954.

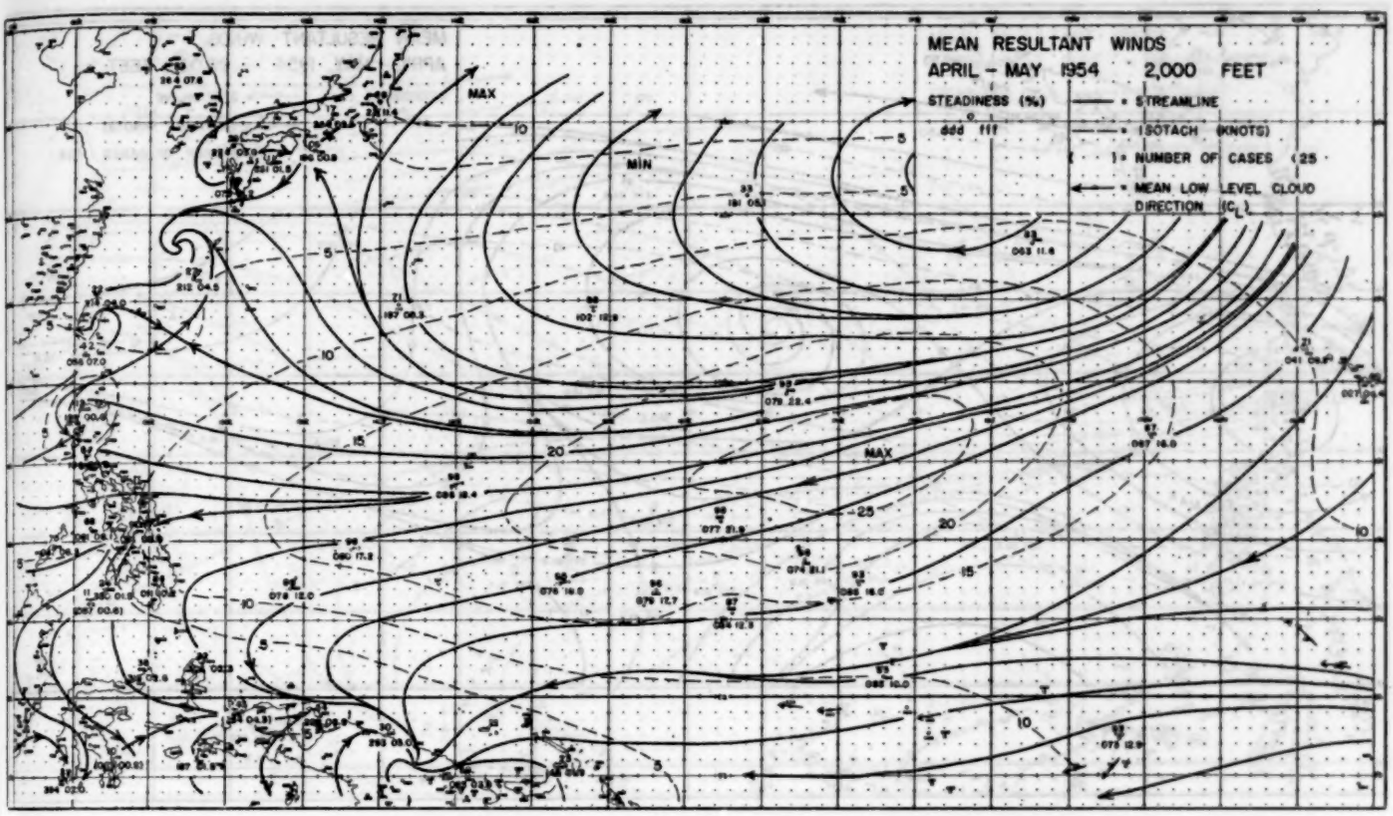

FIGURE 18.—The field of motion at 2,000 feet, April 16–May 15, 1954.

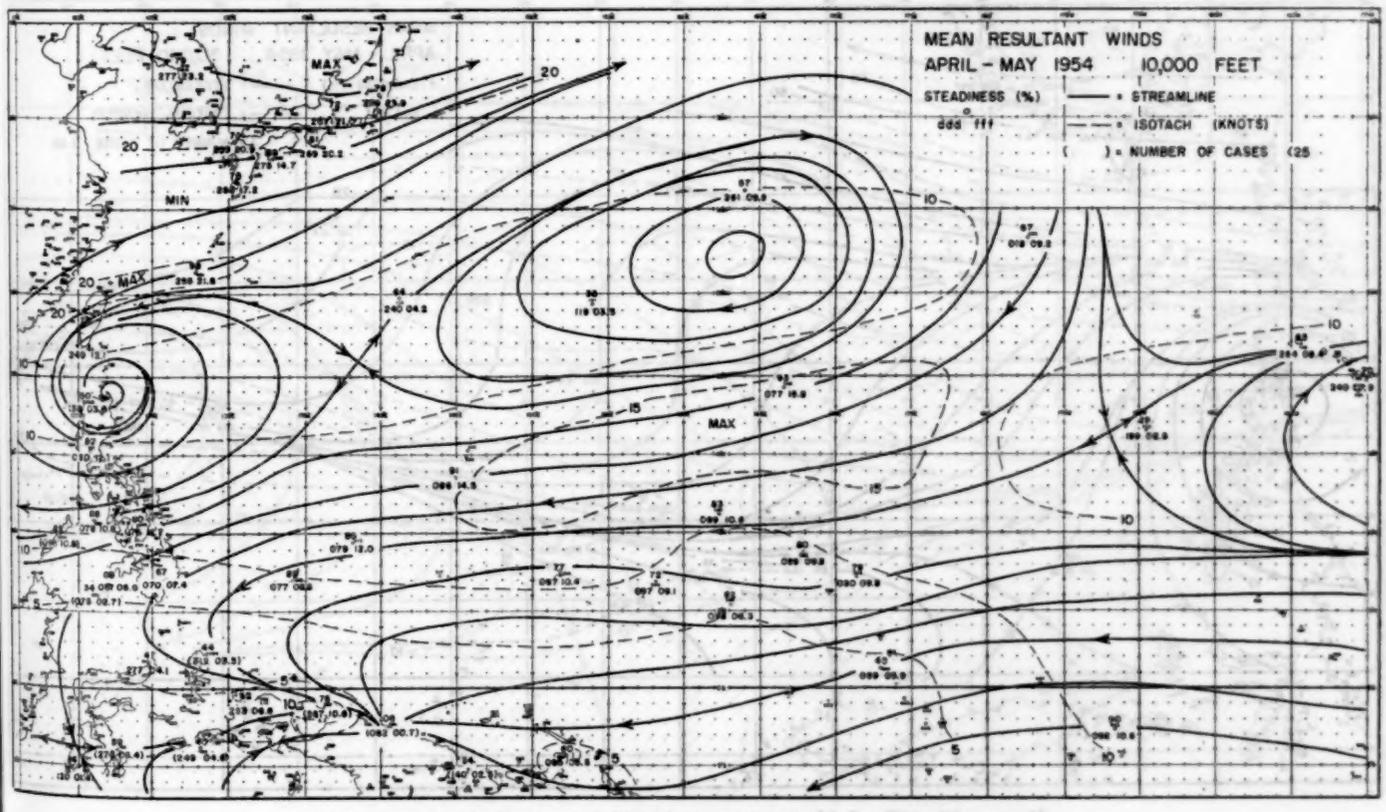

FIGURE 19.—The field of motion at 10,000 feet, April 16–May 15, 1954.

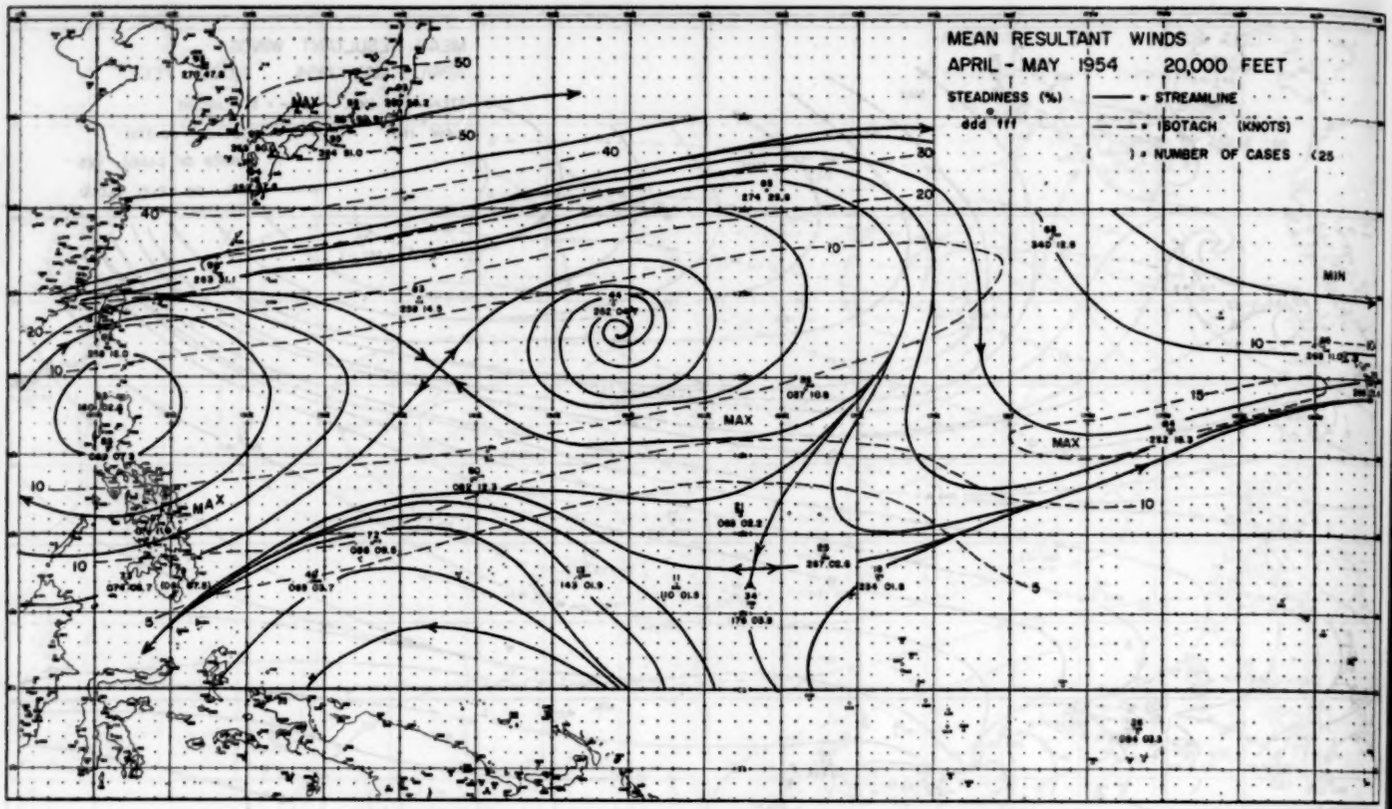

FIGURE 20.—The field of motion at 20,000 feet, April 16–May 15, 1954.

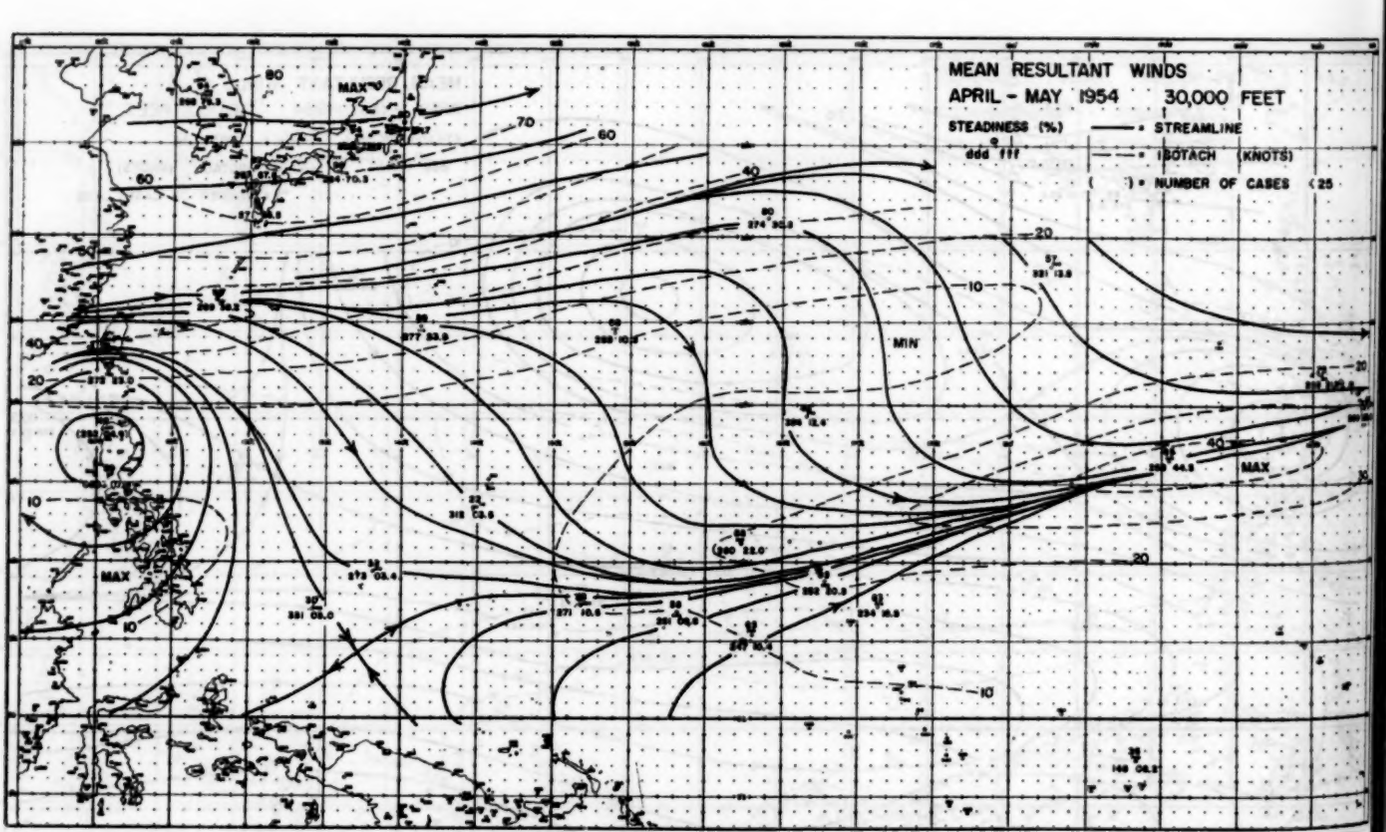

FIGURE 21.—The field of motion at 30,000 feet, April 16–May 15, 1954.

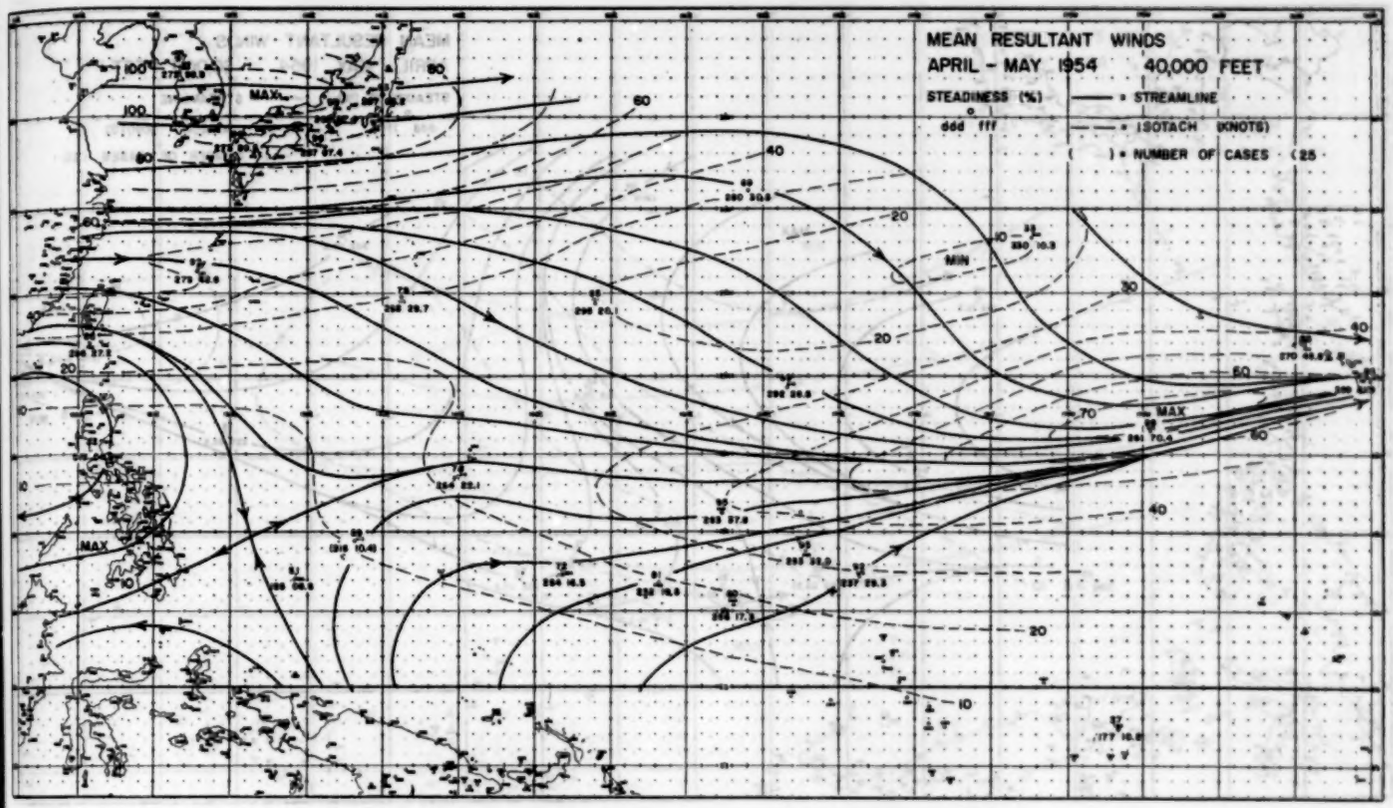

FIGURE 22.—The field of motion at 40,000 feet, April 16–May 15, 1954.

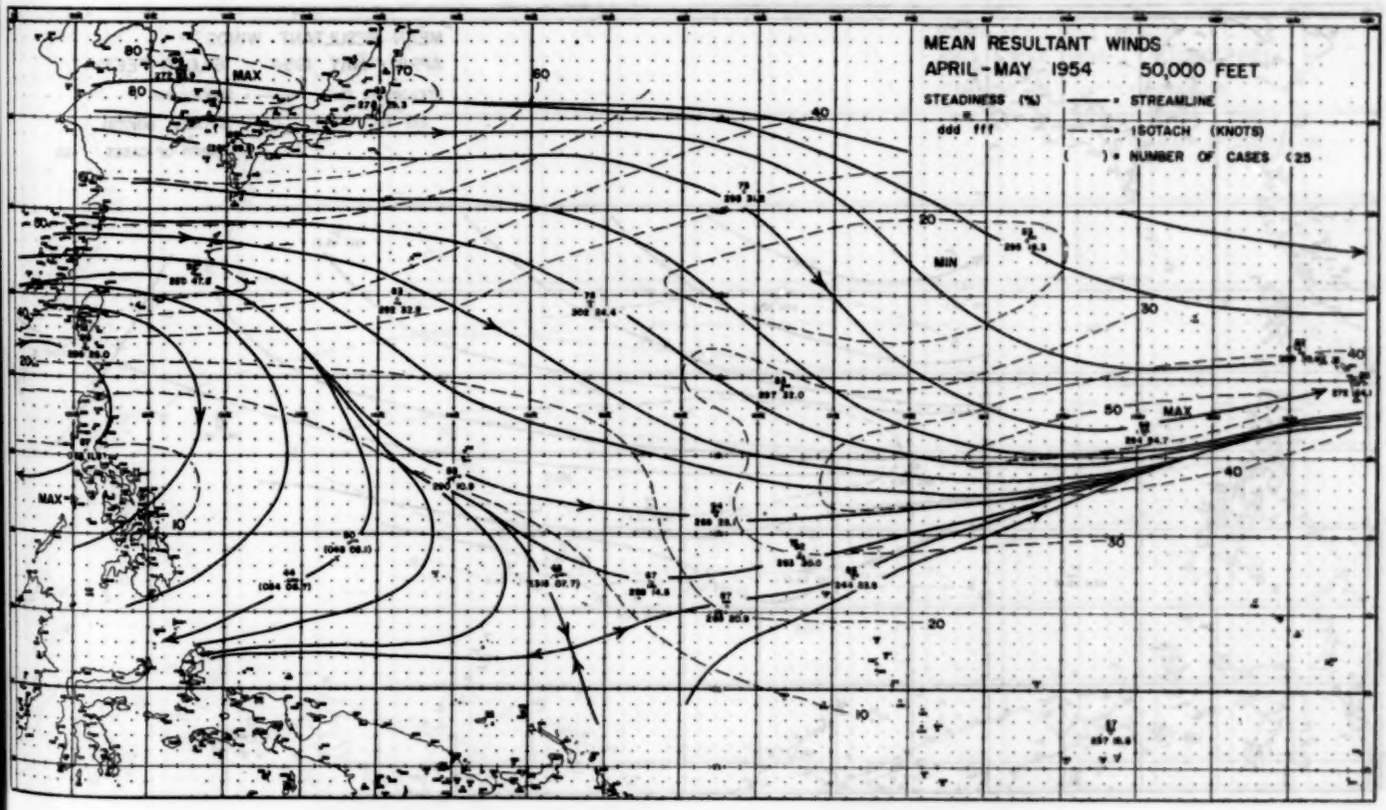

FIGURE 23.—The field of motion at 50,000 feet, April 16–May 15, 1954.

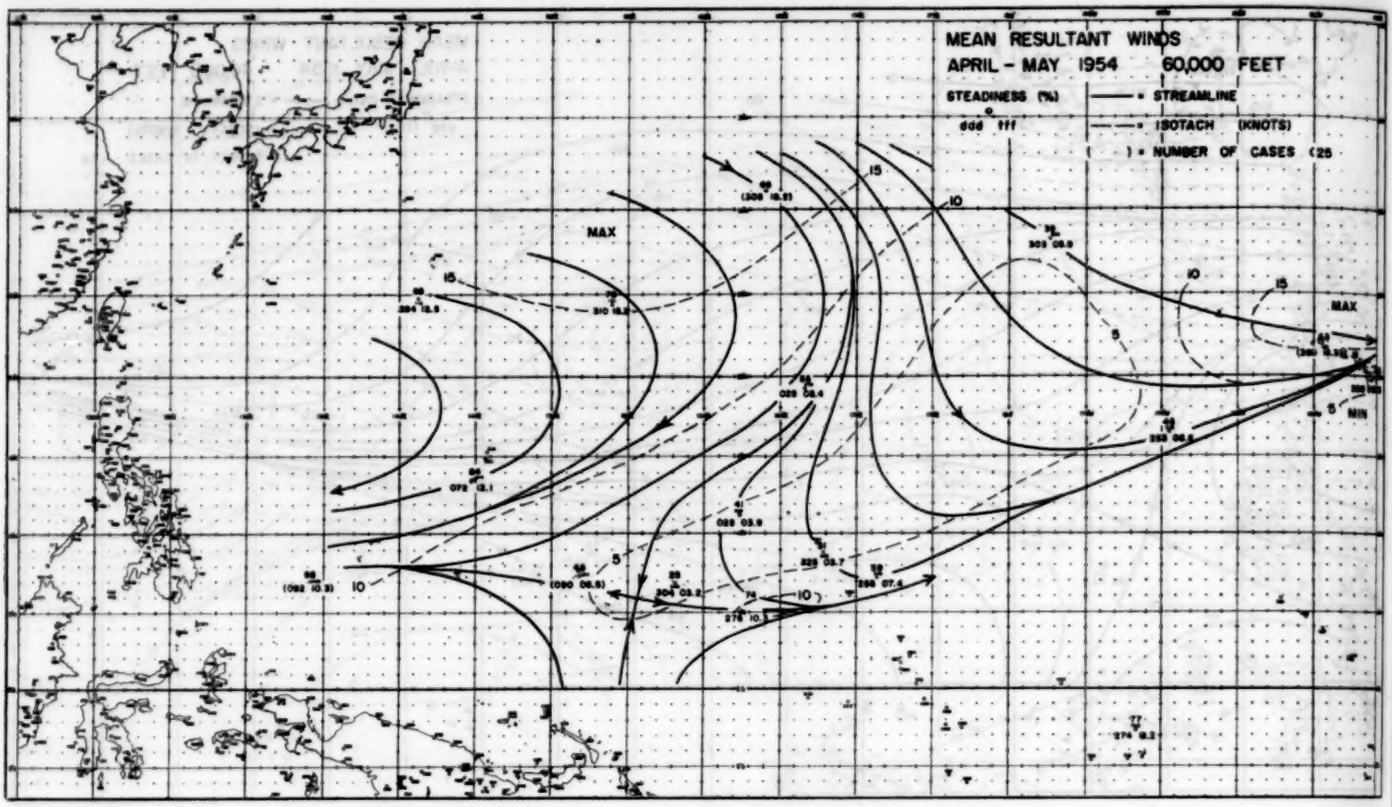

FIGURE 24.—The field of motion at 60,000 feet, April 16–May 15, 1954.

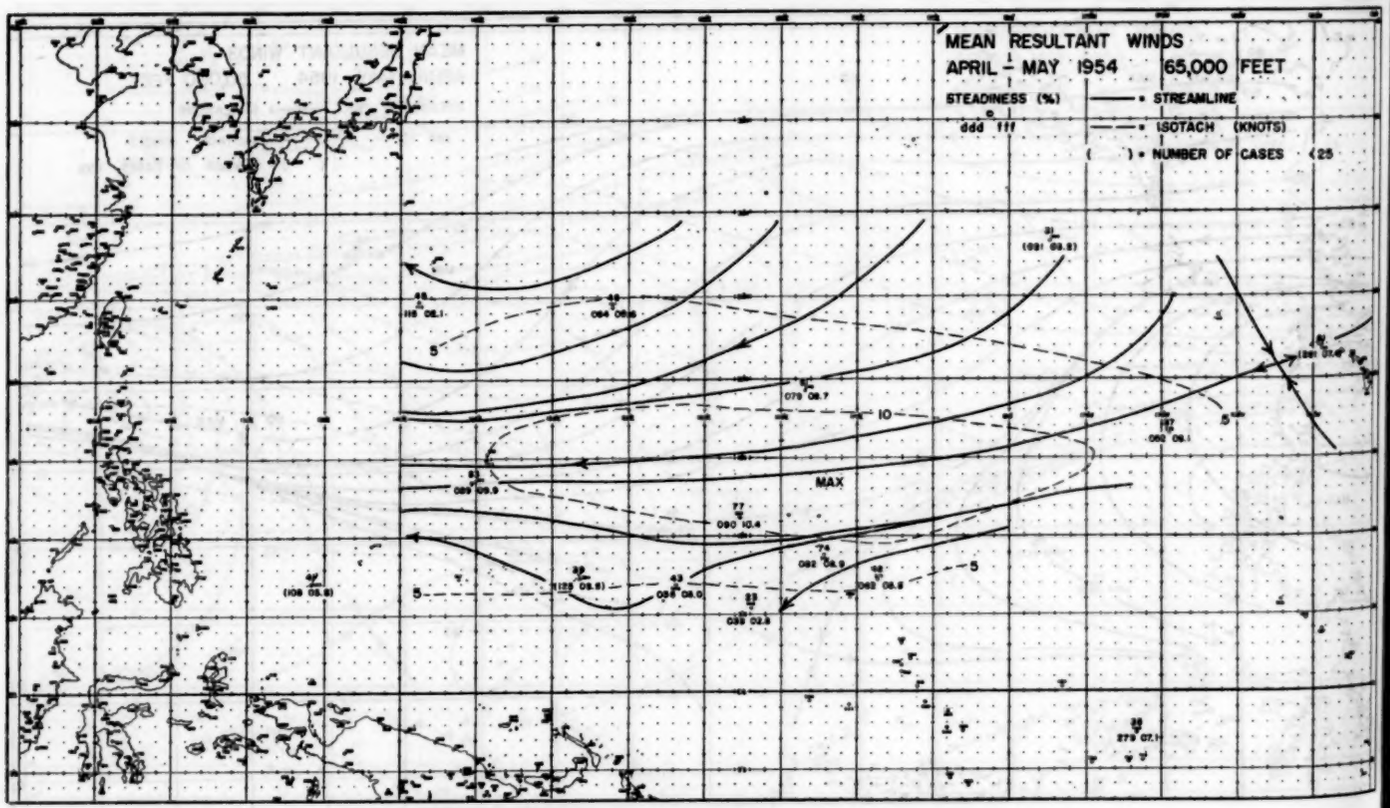

FIGURE 25.—The field of motion at 65,000 feet, April 16–May 15, 1954.

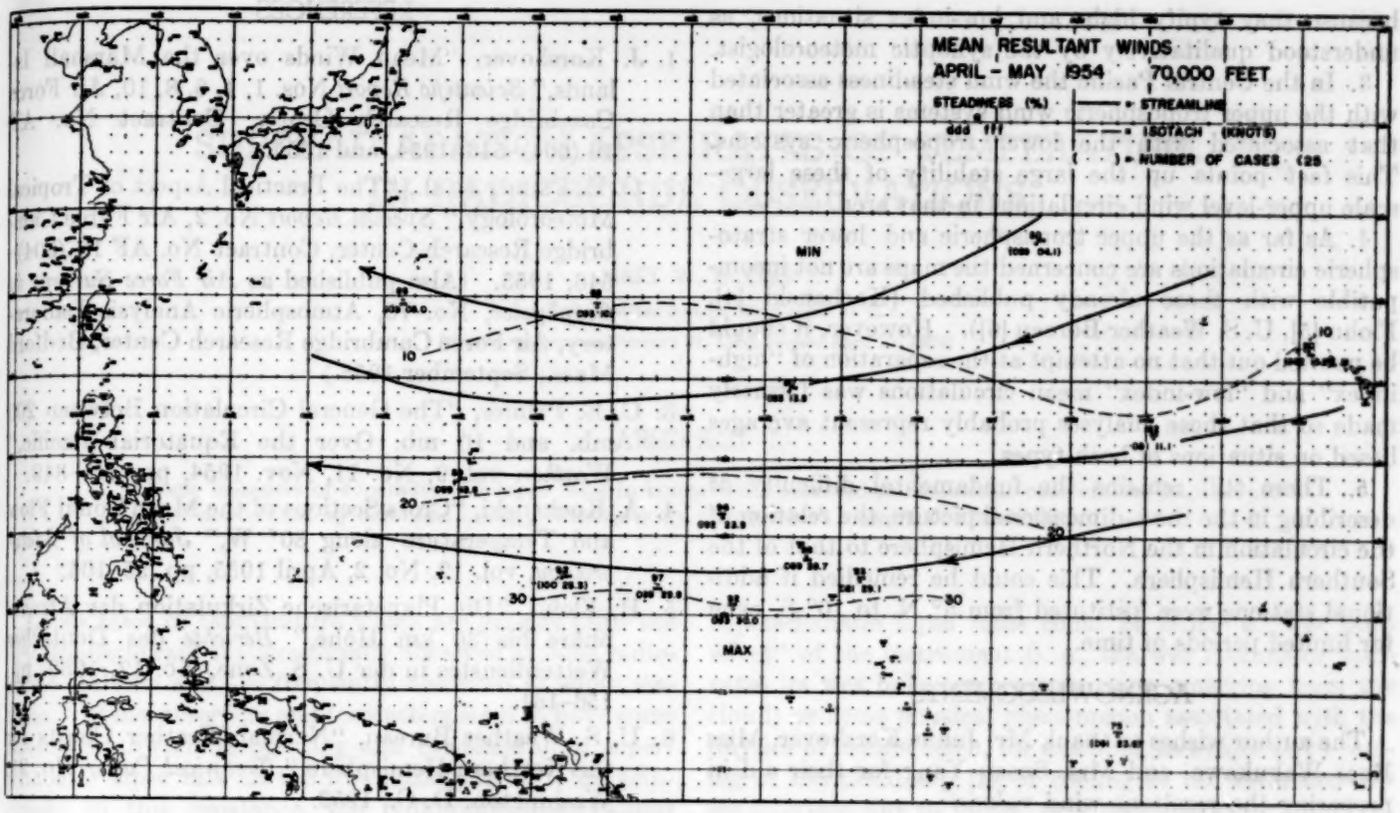

FIGURE 26.—The field of motion at 70,000 feet, April 16–May 15, 1954.

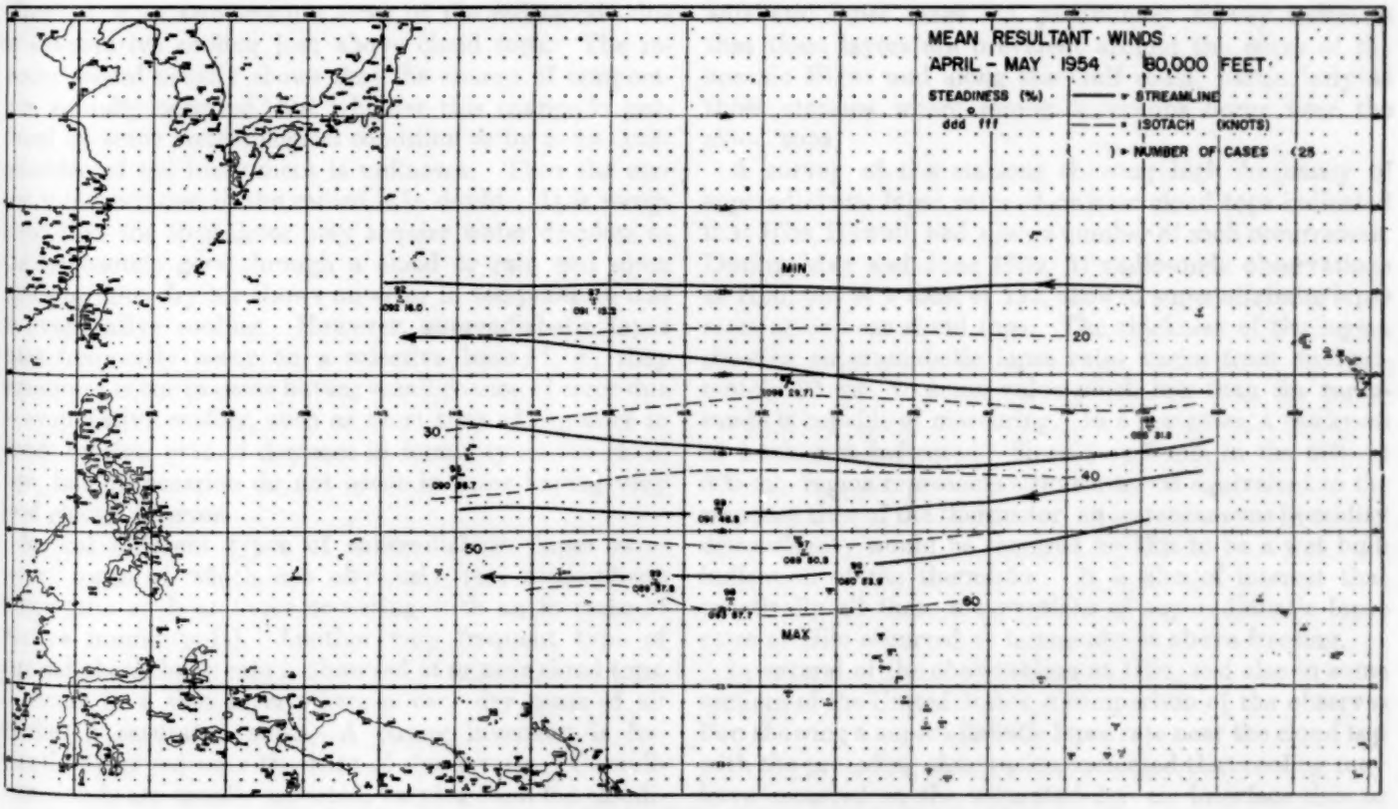

FIGURE 27.—The field of motion at 80,000 feet, April 16–May 15, 1954.

because they typify high- and low-index situations, as understood qualitatively by the synoptic meteorologist.

3. In the Central Pacific the wind steadiness associated with the upper tropospheric wind systems is greater than that associated with the lower tropospheric systems. This fact points up the large stability of these large-scale upper-level wind circulations in that area.

4. As far as the upper tropospheric and lower stratospheric circulations are concerned the maps are not incompatible with those already published (Kochanski [4], Flohn [5], U. S. Weather Bureau [6]). However, it should be pointed out that no attempt at the separation of "high-index" and "low-index" mean circulations was formerly made so that those analyses probably represent averages based on situations of both types.

5. There still remains the fundamental difficulty of describing in the three-dimensional picture, the relation of the circulation in the Northern Hemisphere to that of the Southern Hemisphere. This could be remedied if additional stations were instituted from 5° N. to 10° S. even for limited periods of time.

ACKNOWLEDGMENTS

The author wishes to thank Mr. Julius Korshover, Miss Rose Wakukawa, and Mrs. Susan Yang for their aid in preparing the resultant wind values.

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SUPERADIABATIC LAPSE RATES OF TEMPERATURE IN RADIOSONDE OBSERVATIONS

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[Manuscript received January 31, 1956; revised April 10, 1956]

ABSTRACT

Some instances of superadiabatic lapse rates in temperature observed in radiosonde observations may be produced or accelerated by adiabatic lifting. Examples are shown which suggest this possibility.

Lapse rates of temperature which are greater than the dry adiabatic rate are occasionally observed at most radiosonde stations and are frequently observed at some stations. Many observers and forecasters seem to have some resistance toward recognizing the existence of a superadiabatic lapse rate in the free atmosphere. Due principally to this resistance, the radiosonde observations showing superadiabatic lapse rates have frequently been attributed to some error on the part of the observer or to some defect or characteristic of the radiosonde, the most common of which has come to be called the "wet bulb effect"; i. e., a temperature error of the radiosonde due to evaporative cooling just above cloud tops. The recorder record usually shows that the change of temperature actually occurred, but whether this change is produced by some meteorological condition or by some characteristic of the instrument is unknown. Thus the correct interpretation of the record is in doubt. It is recognized that the thermistor may acquire water droplets as the radiosonde goes through a cloud or rain and upon emerging into dry air shows an error in temperature due to evaporative cooling. However, superadiabatic lapse rates frequently occur on a selective basis; i. e., they sometimes occur in cases having small chance of error due to evaporative cooling, such as short time of exposure to clouds or slow rate of decrease in humidity at the cloud tops, but on occasion do not occur in cases having very good chance of error.

Several different types of superadiabatic lapse rates occur, some of which are obviously real atmospheric phenomena such as those occurring with an increase of relative humidity [1]. Another very frequent type of superadiabatic lapse rate is observed at or near cloud tops. It occurs in a thin layer where a very dry mass of air overlies a saturated mass. A strong inversion is frequently observed near the base of the dry air. Cumuliform clouds are usually reported, varying from 0.3 cloudiness to overcast. It is generally recognized that these superadiabatic lapse rates could be either a "wet bulb effect" of the instrument (i. e., the wet thermistor indicates its wet bulb temperature upon emerging from the cloud) or some physical phenomenon associated with the physics of clouds (such, for example, as evaporative cooling of the cloud top [2], or cooling at the saturated-dry air interface due to lifting, or a combination of these effects). That the rapid changes of temperature seem to occur at times when a dry mass of air overlies a saturated or near-saturated layer of warm air implies a geographical distribution of the stations showing layers with superadiabatic lapse rates. A preliminary survey indicates that these layers are prevalent around the edges of the oceanic Highs and along the Gulf coast, particularly at those stations where strong inversions occur near the cloud tops.

A survey of the stations showing high frequency of superadiabatic lapse rates at or near cloud tops indicated that Hilo, Hawaii, had a large number of such occurrences. During May and June 1950, 51 radiosonde observations at Hilo, out of a total of 122, showed superadiabatic lapse rates at or near cloud tops. The thickness of the layers showing superadiabatic lapse rates varies from approximately 30 mb. to some value much less than the radiosonde is capable of measuring. In a few cases, a thickness of 4 mb. was indicated. Since 4 or 5 mb. in the 600- to 800-mb. region represents a time interval equivalent to the response time of the thermistor, an instantaneous humidity discontinuity would be required for this to be a wet bulb indication of the thermistor. It is also of interest that practically all these observations of superadiabatic lapse rates at Hilo occurred at temperatures above freezing.

In several of the observations at Hilo, and also in some sections of the United States, a comparison of the observation showing a superadiabatic lapse rate near the cloud top with the preceding observation indicated that cooling may have occurred at the saturated-dry air interface due to adiabatic lifting between the two observations. Hilo

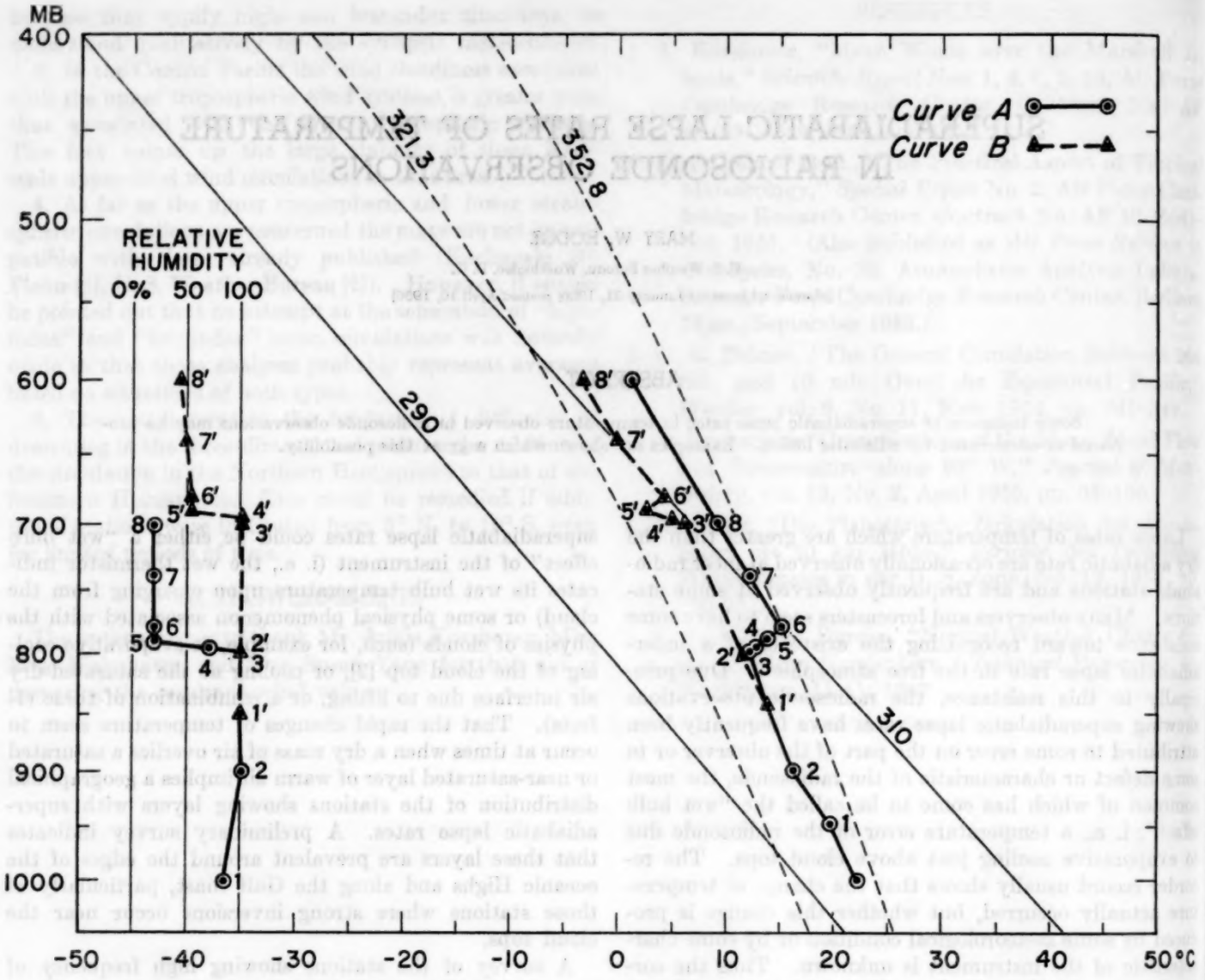

FIGURE 1.—An assumed observation (Curve A) when lifted adiabatically without change produces Curve B.

offers an excellent example where orographic lifting may occur frequently and may be a contributing factor in producing many of the superadiabatic lapse rates.

Assume a pressure, temperature, humidity relationship such as that shown in Curve A, figure 1. If the layer of air between levels 1 and 7 is lifted adiabatically 100 mb. (lift the dry air along the dry adiabatic lapse rate until saturated and then along the saturated adiabatic lapse rate, and lift the saturated air along the saturated adiabatic lapse rate), the pressure-temperature curve shown in Curve B results, assuming no changes other than those due to adiabatic lifting. A superadiabatic lapse rate will be produced in a thin layer of air just above the saturated air mass.

Figures 2 and 3 show two pairs of successive radiosonde observations at Hilo. In each case the first observation is shown as Curve A, the following observation as Curve B dashed line. If that portion of the air mass indicated by the numbers is lifted adiabatically, assuming the layer of the air at the base of the inversion is saturated before lifting begins, Curve C, solid line, results. (Point 1, Curve A, is lifted to 1′, Curve C; 2 to 2′, etc.) The similarity between the calculated sounding, Curve C, and the observed second sounding, Curve B, is striking. In each case the amount of lifting assumed is indicated on the figure. It seems reasonable to assume that a small layer of air near the base of the inversion is saturated before lifting began since in each case low clouds are reported at the first observation.

Cooling due to adiabatic lifting is offered as a suggested explanation for at least part of the cooling effect observed in some of the superadiabatic lapse rates near cloud tops.

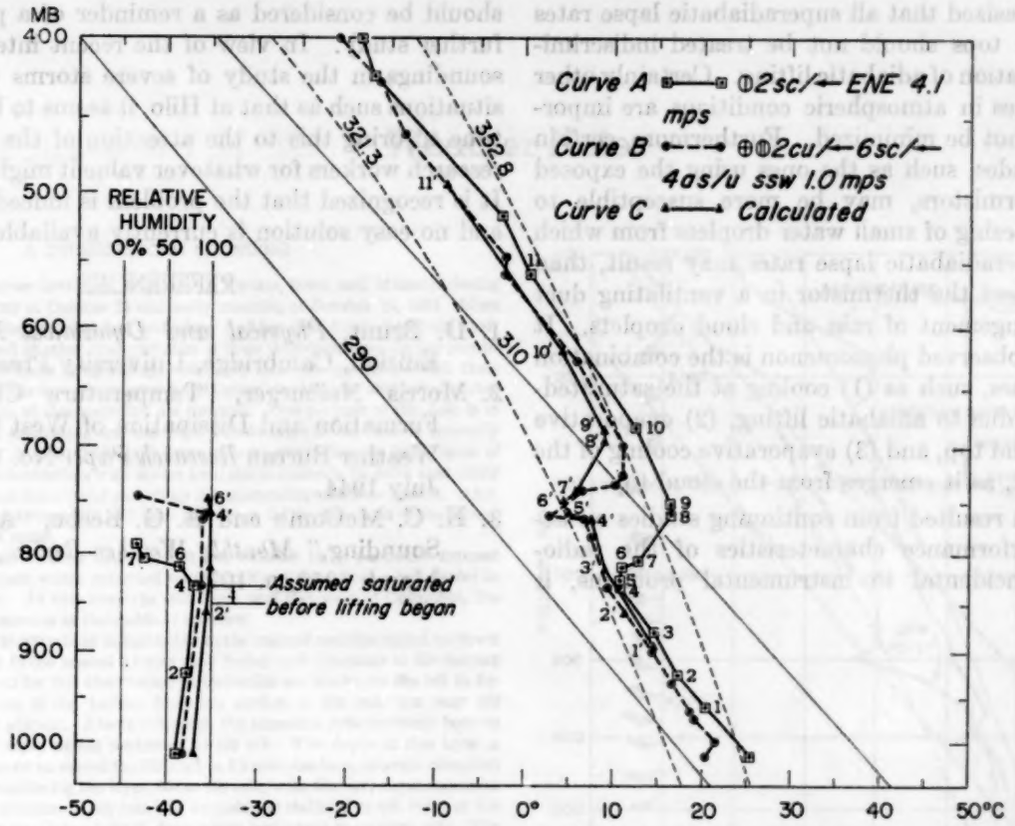

FIGURE 2.—Two successive soundings at Hilo, Hawaii. If the earlier sounding is lifted adiabatically 65 mb. a calculated sounding result which is similar to the later observation. Curve A: June 17, 1950, 0300 GMT. Curve B: June 17, 1950, 1500 GMT. Curve C: Calculated

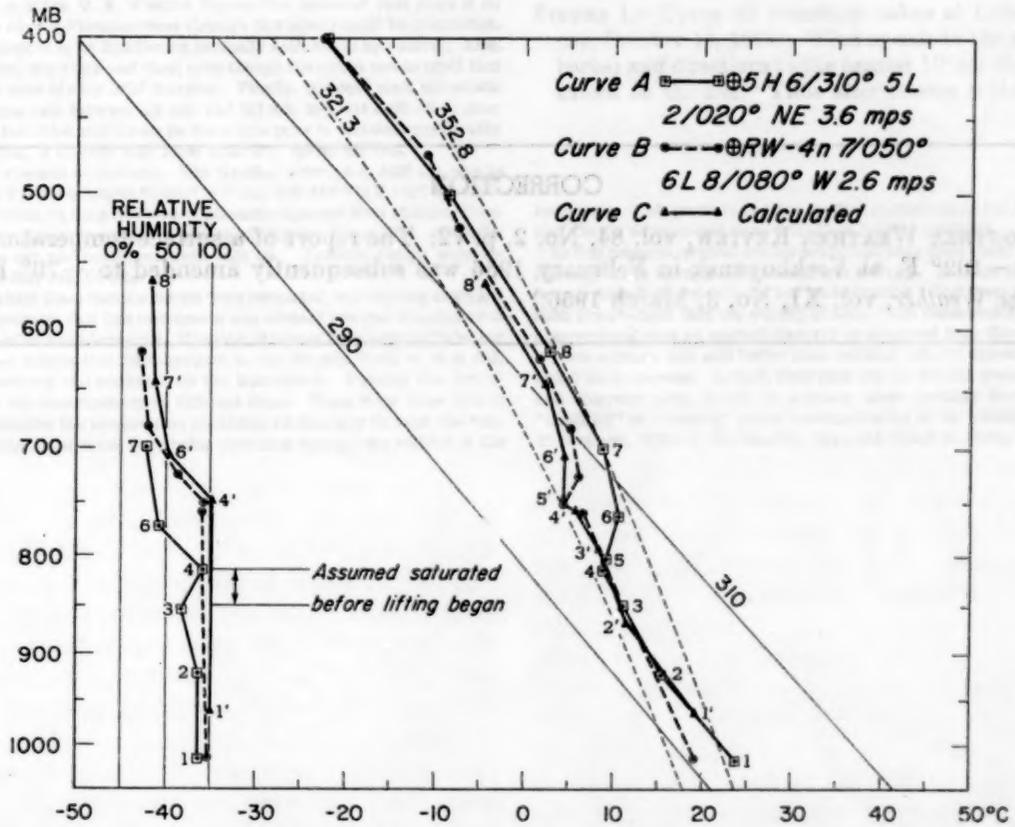

FIGURE 3.—Two successive soundings at Hilo, Hawaii. If the earlier sounding is lifted adiabatically 55 mb., a calculated sounding results which is similar to the later observation. Curve A: May 3, 1950, 0300 GMT. Curve B: May 3, 1950, 1550 GMT. Curve C: Calculated.

It must be emphasized that all superadiabatic lapse rates at or near cloud tops should not be treated indiscriminately as an indication of adiabatic lifting. Certainly other concurrent changes in atmospheric conditions are important and should not be minimized. Furthermore, certain types of radiosondes, such as the ones using the exposed white-coated thermistors, may be more susceptible to collecting and freezing of small water droplets from which instrumental superadiabatic lapse rates may result, than those which protect the thermistor in a ventilating duct from direct impingement of rain and cloud droplets. It may be that the observed phenomenon is the combination of several processes, such as (1) cooling at the saturated-dry air interface due to adiabatic lifting, (2) evaporative cooling at the cloud top, and (3) evaporative cooling of the thermistor, if wet, as it emerges from the cloud top.

This discussion resulted from continuing studies on accuracies and performance characteristics of the radiosonde. Being incidental to instrumental problems, it should be considered as a reminder of a phenomenon for further study. In view of the recent interest in unusual soundings in the study of severe storms [3] and in local situations such as that at Hilo, it seems to be an opportune time to bring this to the attention of the forecasters and research workers for whatever value it might have to them. It is recognized that the problem is indeed a complex one and no easy solution is currently available.

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3. H. C. McComb and R. G. Beebe, "A Thunderstorm Sounding," *Monthly Weather Review*, vol. 84, No. 3, March 1956, p. 107.

CORRECTION

MONTHLY WEATHER REVIEW, vol. 84, No. 2, p. 72: The report of a surface temperature of −102° F. at Verkhoyansk in February 1956 was subsequently amended to −70° F. (See *Weather*, vol. XI, No. 3, March 1956.)

Weather Notes

A THUNDERSTORM SOUNDING

An area of thunderstorms developed over eastern Kansas, Iowa, and Missouri during the afternoon and evening of October 13 and early morning of October 14, 1954. Most of these thunderstorms formed ahead of and along a sharp cold front; however, their scattered locations, as well as other characteristics of these thunderstorms, do not permit an analysis of their occurrences along a single instability line. In connection with these thunderstorms, a special RAOB was requested from Columbia, Mo., for 0300 CST, October 14, 1954. Several features of this sounding are unusual. One purpose of this note is to point out some of these interesting features with a little more detail than is generally available in such cases. A more important purpose is to emphasize the importance of this type of sounding in connection with severe local storm research, in order that every effort will be made to evaluate similar soundings in a reasonable amount of detail. Also, it is hoped that RAOB observers will call such soundings to the attention of the Severe Local Storms Forecast Center.

A feature of the surface weather map for 0030 CST, October 14, of particular interest here, was a sharp cold front which extended south-southwestward from a low center in southwestern Wisconsin. At this time the cold front was just west of Columbia, the actual frontal passage occurring at Columbia at 0505 CST.

The plotted sounding to 400 mb. as computed from the original recorder record is shown in figure 1. Wind speeds to the nearest 5 knots (half barbs) and directions to the nearest 10° for the standard levels for this observation at Columbia are shown on the left in figure 1. The rate of ascent of the balloon from the surface to 604 mb. was near 950 ft./min., which is about average. Above this level, the ascension rate suddenly became much greater, and this rapid ascent continued to 436 mb. The depth of this layer is 8,890 ft., and the instrument traversed the distance in 3.2 minutes for an average ascension rate of 2,780 ft./min. Considering the layer, 604 to 436 mb., with the very rapid ascension rate, note that the temperature lapse rate was exceedingly stable through most of the layer, and it was capped by a layer 3,280 ft. deep which had a very steep lapse rate. The decrease of potential temperature through this upper layer was 9° C.

Such unusual lapse rates are usually considered as resulting from instrumental error, or, in the case of a very steep lapse rate through a dry layer, from the wet-bulb effect. The Instrument Division of the U. S. Weather Bureau has indicated that there is no obvious reason why the recorded temperatures through this layer should be questioned, since the instrument appeared to be functioning normally both above and below. Also, the original recorder record was sharp and clear, even though the ascent was so rapid that the baroswitch contacts were of only brief duration. Finally, it would seem unrealistic to attribute the steep lapse rate between 479 mb. and 423 mb. to a wet-bulb effect since the layer was over 3,000 feet thick and the air for some time prior to this was considerably less than saturated. Thus, it appears that these measured values are real.

This instrument was released at 0237 CST. The weather reported at 0228 CST was as follows: RS2 M50 ⊕ 2 1/2 TRW+054/66/64/↗9/971/T SW and NW MOVG E FQT LTGIC-CG SW THRU N. Distant lighting had been continually reported from 1905 CST, October 13, until thunder was finally heard at the station at 0105 CST, October 14. Thunder with rain started at 0105 CST, and continued until 0559 CST. Pressure jumps were reported at 0053, 0448, and 0527 CST, October 14.

The cold front, with which these thunderstorms were associated, was moving eastward about 20 m. p. h. It is probable that this instrument was released into one thunderstorm that was surrounded by other thunderstorms. However, it cannot be ascertained whether the instrument remained within this thunderstorm to the 400-mb. level, or, if it did, what part of the thunderstorm was traversed by the instrument. Possibly the instrument was in and out of the thunderstorm at different times. Thus, from these data it cannot be determined whether the temperature gradients, particularly through the very steep and/or the very stable lapse rates, were being measured through the vertical or the horizontal. This problem is being studied in research at the Severe Local Storms Forecast Center as more and more soundings become available.

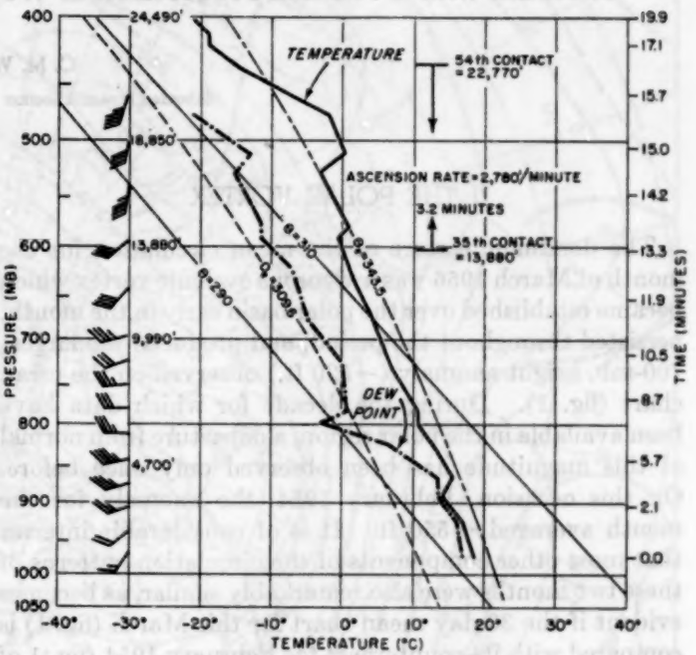

FIGURE 1.—Upper air soundings taken at Columbia, Mo., at 0237 CST, October 14, 1954. Wind speeds to the nearest 5 knots (half barbs) and directions to the nearest 10° for the standard levels are shown on the left. Time after release is shown on the right.

In this research, several similar soundings have been noted when the instrument was released in the vicinity of thunderstorm activity. Perhaps these unusual lapse rates in or near thunderstorms should not be surprising. But there are at least two features of such observations that are worthy of note. The more important of these is that direct observational data on updraft strength as measured from the ascension rate, admittedly a gross estimate but still better than nothing, are not currently being included in the coded RAOB message. Indeed, such data are not usually evaluated. Finally, forecasters and observers alike should be cautious about terming unusual temperature data as "doubtful" or "missing" unless malfunctioning of the instrument is apparent.—*Harold C. McComb, WBAS, Kansas City, Mo., and Robert G. Beebe, WBFC, Kansas City, Mo.*

THE WEATHER AND CIRCULATION OF MARCH 1956 [1]

A Month with a Marked Progression of Weekly Temperature and Circulation Anomalies

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1. THE POLAR VORTEX

The dominant feature of the mean circulation for the month of March 1956 was a vigorous cyclonic vortex which became established over the polar basin early in the month, persisted throughout the period, and produced the largest 700-mb. height anomaly (−520 ft.) observed on the mean chart (fig. 1). During the decade for which data have been available in the polar region, a departure from normal of this magnitude has been observed only once before. On this occasion, February 1954, the anomaly for the month averaged −550 ft. It is of considerable interest that most other components of the circulation patterns of these two months were also remarkably similar, as becomes evident if the 30-day mean chart for this March (fig. 1) is compared with its counterpart for February 1954 (fig. 1 of [1]).

2. THE ZONAL INDEX AND JET STREAM

The long and record-breaking persistence (since November 1955) of subnormal zonal index values has been a highlighted topic in several previous articles of this series [2, 3, 4]. However, this trend was finally reversed toward the end of February [5], and the zonal index at 700 mb. for the period February 29–March 4 exceeded the normal by 4.8 m. p. s. Thereafter, strong zonal westerlies governed the circulation during March, averaging 12.1 m. p. s. (3 m. p. s. above normal) for the month.

The axis of the 700-mb. jet stream associated with this flow was near its normal latitude of 45° N., with a sharp profile and strong shear both to the north and south (fig. 2). Figure 3A shows that this narrow belt of fast westerlies circled virtually the whole of the Western Hemisphere, with wind speeds strongest relative to normal (fig. 3B) in the western Atlantic (+8 m. p. s.) and also over a broad zonal expanse of the Pacific (+6 m. p. s). Branching of the jet stream occurred, however, in the central Atlantic as blocking assumed control over Europe. A secondary jet, south of the polar vortex, averaged 7 m. p. s. at about 77° N., about three times the normal wind speed at that latitude (fig. 2).

The flow pattern at 200 mb. (fig. 4) resembled that at the 700-mb. level quite closely, except that a branch of the jet stream separated from the main axis in the western Pacific to dip southeastward toward the Hawaiian Islands and then return northeastward to rejoin the principal current over the United States.

3. THE CIRCULATION REVERSAL

The circulation at the 700-mb. level at middle latitudes for the month of March underwent a fundamental change in planetary wave pattern about midmonth. Consequently the two halves of the month tended to offset each other, resulting in relatively small residual anomalies for the month as a whole over the United States in both 700-mb. height (fig. 1) and surface temperature (Chart I-B). The first half-month (fig. 5A) was roughly a continuation of the high-index pattern which characterized the latter portion of February [5]. The flow was relatively flat and sufficiently fast to support very long planetary waves. In fact, the hemispheric wave number was reduced to 3 at middle latitudes. Of particularly large longitudinal dimension was the wavelength from the Japanese to the United States trough. Note that strong positive tilt from NE to SW typical of high-index flow was characteristic of both these troughs. One remarkable feature of the circulation of this period is the fact that only one closed vortex of any magnitude existed, and that was the polar vortex previously mentioned. It became very intense during this period with a departure from normal of −640 ft. and was instrumental in introducing extremely cold air into Alaska and Canada, as will be considered later. (See sec. 7.)

On the other hand, figure 5B reveals a quite different regime for the second half-month. The zonal index dropped to 10.4 m. p. s., resulting in shorter wavelengths and an increase in hemispheric wave number. This wavelength adjustment was accomplished by the appearance of a trough over the eastern Pacific in almost the same longitude as the ridge in the previous half-month. A similar rearrangement occurred downstream as the ridge progressed well inland over the Rockies, and a full latitude trough developed off the east coast. One additional marked change occurred farther downstream in the eastern Atlantic and Europe. The Eurasian trough, which was so prominent early in the month, proved short-lived,

[1] See Charts I-XV following p. 126 for analyzed climatological data for the month.

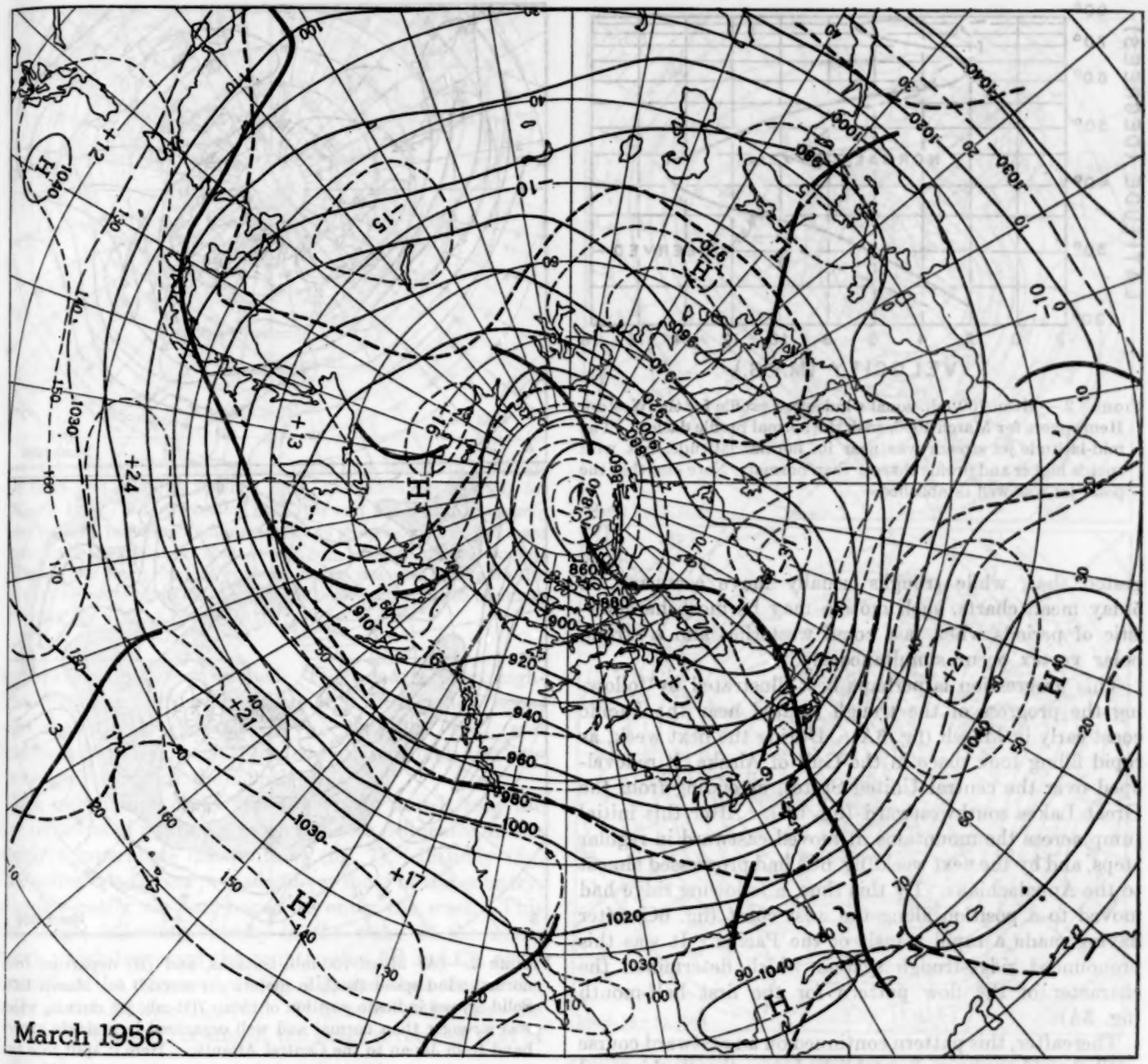

FIGURE 1.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for March 1956. The polar region was the site of the largest anomaly center (−520 ft.) This vortex was the only closed low center of any consequence observed on the mean chart. Elsewhere in the Western Hemisphere anomalies were relatively small, particularly over the United States.

and the pattern of the latter half-month returned to the pronounced blocking regime which strongly dominated Europe during February [5]. The seat of blocking lay over Finland, where an anomaly center of +580 ft. was observed. Several blocking surges proceeded westward from this center during the month. This is attested by the belt of sizeable positive anomaly which extended westward across Greenland and most of Canada. It was one such blocking surge which set the stage for heavy snows in the Northeast. (See sec. 6.)

4. EASTWARD MOTION OF 5-DAY MEAN FEATURES

The circulation reversal described above was the consequence of a fairly regular eastward motion of most 5-day mean circulation components. This progression occurred over the relatively long span of 6 weeks, as illustrated by the series of charts in figure 6. The average 5-day mean trough speed of 6° longitude per week at 45° N. for the winter season over North America [6, 7] was roughly doubled during this period. These considerations sug-

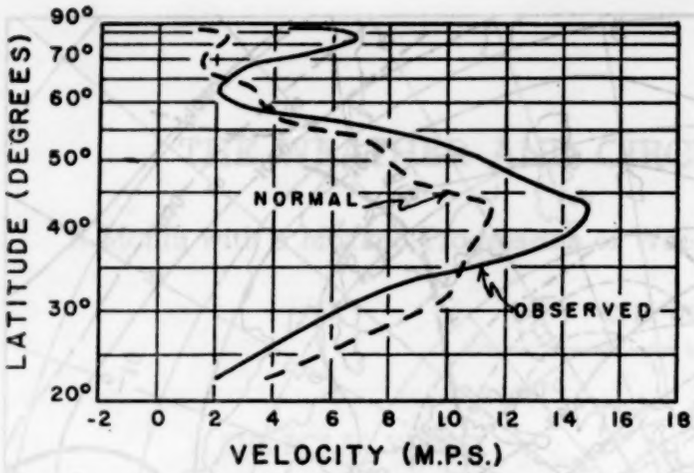

FIGURE 2.—Mean 700-mb. zonal wind speed profile for the Western Hemisphere for March 1956, with the normal profile dashed. The mid-latitude jet stream was near its normal latitude, but with speeds higher and profile sharper than normal. Note also that the polar jet was well established.

gested that, while troughs usually move eastward on 5-day mean charts, such motion may be most characteristic of periods when fast zonal westerlies and a strong polar vortex occur simultaneously.

This progression is perhaps best illustrated by following the progress of the trough located near the Pacific coast early in March (fig. 6A). During the next week, as rapid filling took place in the Gulf of Alaska, it redeveloped over the central United States, extending from the Great Lakes southwestward (fig. 6B). After this initial jump across the mountains, it moved eastward in regular steps, and by the next week (fig. 6C) had progressed almost to the Appalachians. By this time, a following ridge had moved to a position along the west coast (fig. 6C) after having made a rapid transit of the Pacific. It was this pronounced ridge-trough system which determined the character of the flow pattern for the first half-month (fig. 5A).

Thereafter, this pattern continued on an eastward course until the ridge was well established over the Rockies and the trough well off the east coast (fig. 6D). This was the dominant pattern previously described for the second half of the month (fig. 5B). It should be noted that another trough had appeared in the Gulf of Alaska during this period (fig. 6D) after having similarly made rapid progress across the Pacific.

By month's end (fig. 6E) the pattern became complicated by the advent of blocking over the North Atlantic and Canada which shortened the wavelength and rendered the continuity less straightforward. Nonetheless, progressive motion can still be ascribed to the Pacific trough, which moved inland, and to the Atlantic coastal trough, which moved slightly farther east. Meanwhile, a new trough developed to the lee of the Rocky Mountains, thus creating a short wavelength.

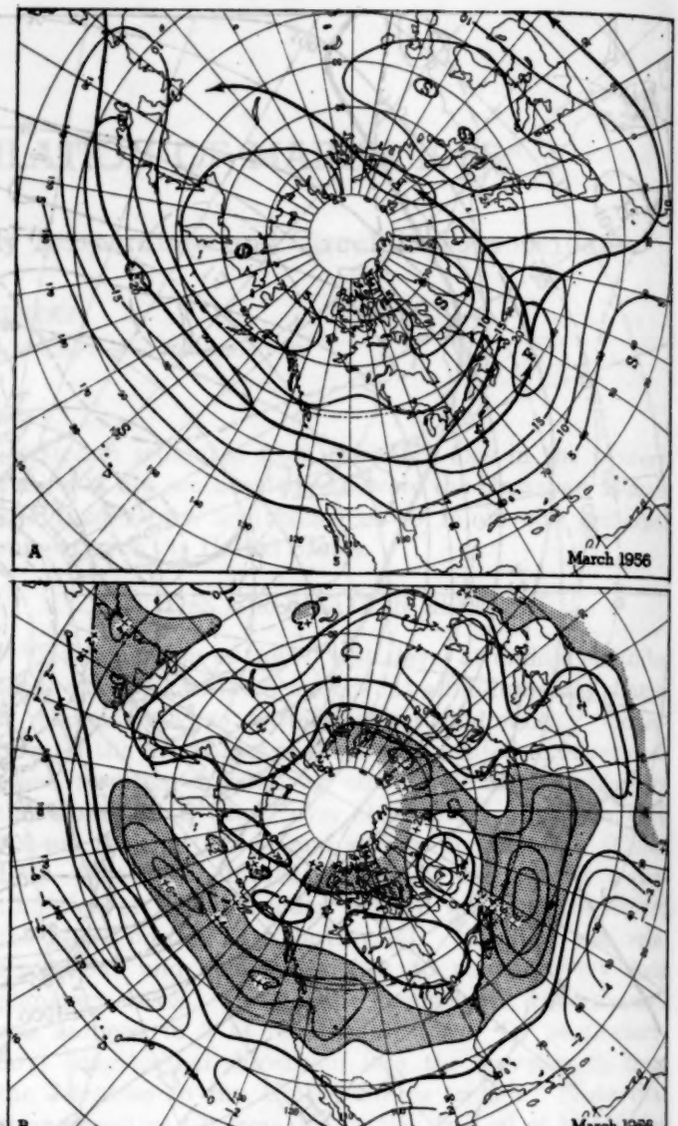

FIGURE 3.—(A) Mean 700-mb. isotachs, and (B) departure from normal wind speed (both in meters per second) for March 1956. Solid arrows indicate position of mean 700-mb. jet stream, which was stronger than normal and well organized in a single narrow band from Japan to the Central Atlantic. Here it split into two branches, one to the north and the other to the south of blocking over Europe.

The chart for the first week in April (fig. 6F) has been included, since by this time a full cycle had been completed over the United States, as this pattern closely resembles that for the corresponding period in March (fig. 6B). Also, eastward motion is still discernible, though it is mainly limited to lower latitudes because of the blocking over Canada. A sequence somewhat similar to this has been described by Namias using a series of monthly mean charts [7].

5. THE TEMPERATURE REGIME

As the series of planetary waves described in the preceding section traversed the United States, radically differing

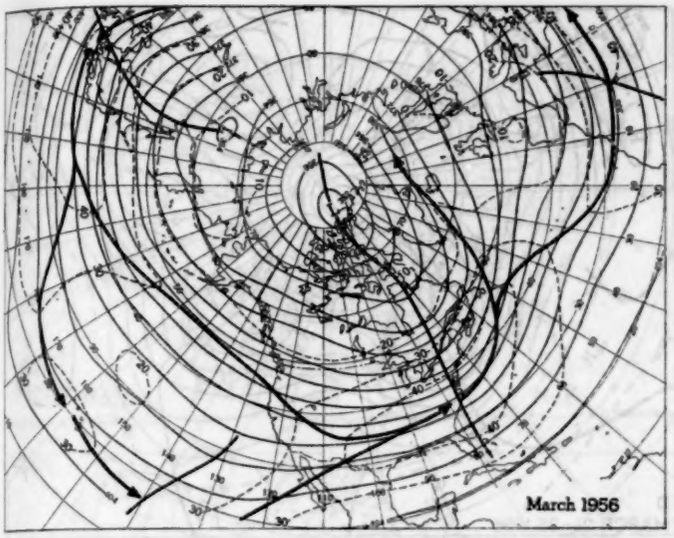

FIGURE 4.—Mean 200-mb. contours (solid lines labeled in hundreds of feet) and isotachs (dashed lines, in meters per second) for March 1956. The westerlies were fast and flat with a very long wavelength between minimum-latitude troughs. The jet-stream pattern was similar to that at 700 mb., except that a tropical branch left the principal current in the western Pacific to dip southward over the Hawaiian Islands before returning to the main jet over the United States.

temperature regimes developed. These contrasts are highlighted by the odd circumstance that such widely separated stations as Sheridan, Wyo., Amarillo, Tex., and Schenectady, N. Y., each recorded both new high and new low temperatures for the month.

The half-month oscillation previously noted from the flow patterns of figure 6 was even better delineated in the weekly temperature distributions (fig. 7). Initially (fig. 7A), warm conditions prevailed over most of the country, although cooler air had begun to enter the west. This cold surge, following rapidly in the wake of the mean trough which traversed the country (fig. 6B and C), overspread first the western half (fig. 7B) and then almost the whole of the Nation (fig. 7C). It is noteworthy that the pattern in figure 7C is almost the exact reverse of that of figure 7A.

TABLE 1.—*Record-breaking temperatures during the first half of March 1956*

Station	Temperature (° F.)	Date
A—Minima		
Yuma, Ariz.	33	13
Santa Maria, Calif.	29	5
Amarillo, Tex.	9	12
Missoula, Mont.	−5	11
Sheridan, Wyo.	−18	11
B—Maxima		
Wichita Falls, Tex.	92	5
Norfolk, Va.	83	7
Topeka, Kans.	83	5
Cincinnati, Ohio	75	5
Schenectady, N. Y.	50	2

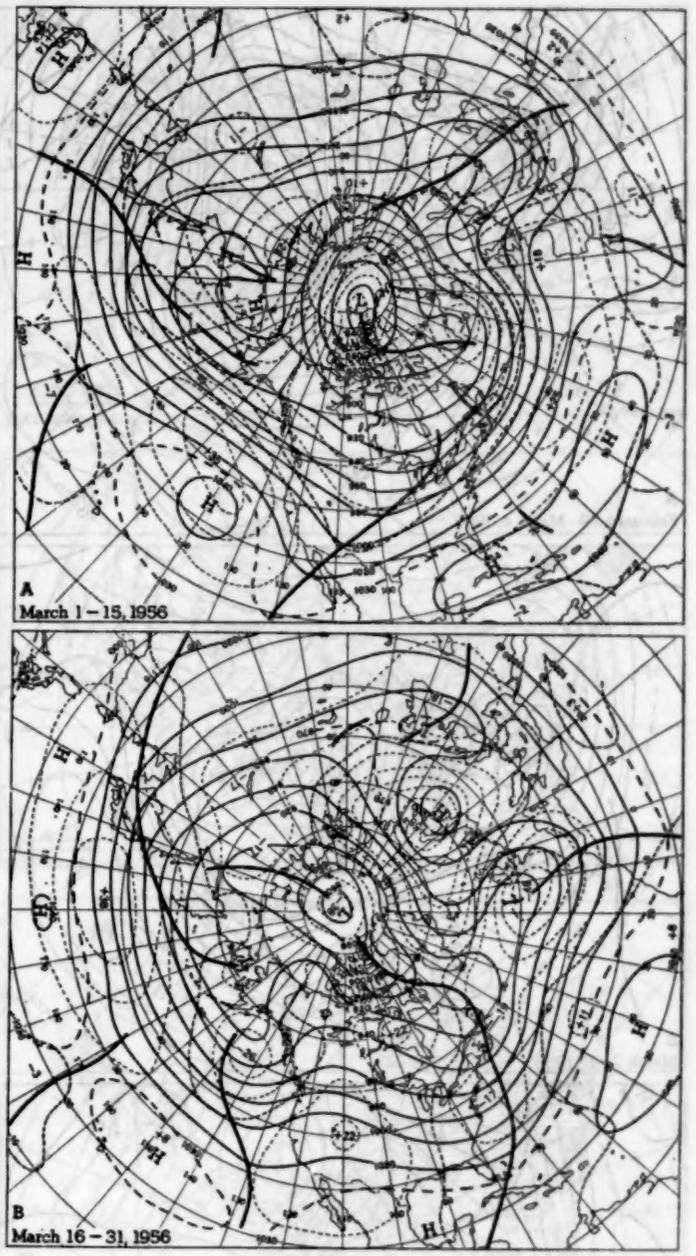

FIGURE 5.—700-mb. height contours and departures from normal (in tens of feet) (A) March 1–15, 1956, and (B) March 16–31, 1956. The circulation for the first half-month manifested the features typical of high index: westerlies of high speed and small amplitude with very long wavelength. The zonal index diminished in the second part of the month, requiring an increase in hemispheric wave number. The adjustment in circulation pattern incident to this change markedly altered the flow pattern over North America.

During this sequence, as the intense cold outbreak replaced the warm regime, several new records were established for temperature minima in the West and maxima in the East. A few are listed in table 1.

Thereafter the mean ridge moved inland over the Rockies (fig. 6D), flooding the West with a broad and unusually warm current to its rear (fig. 7D). This warm

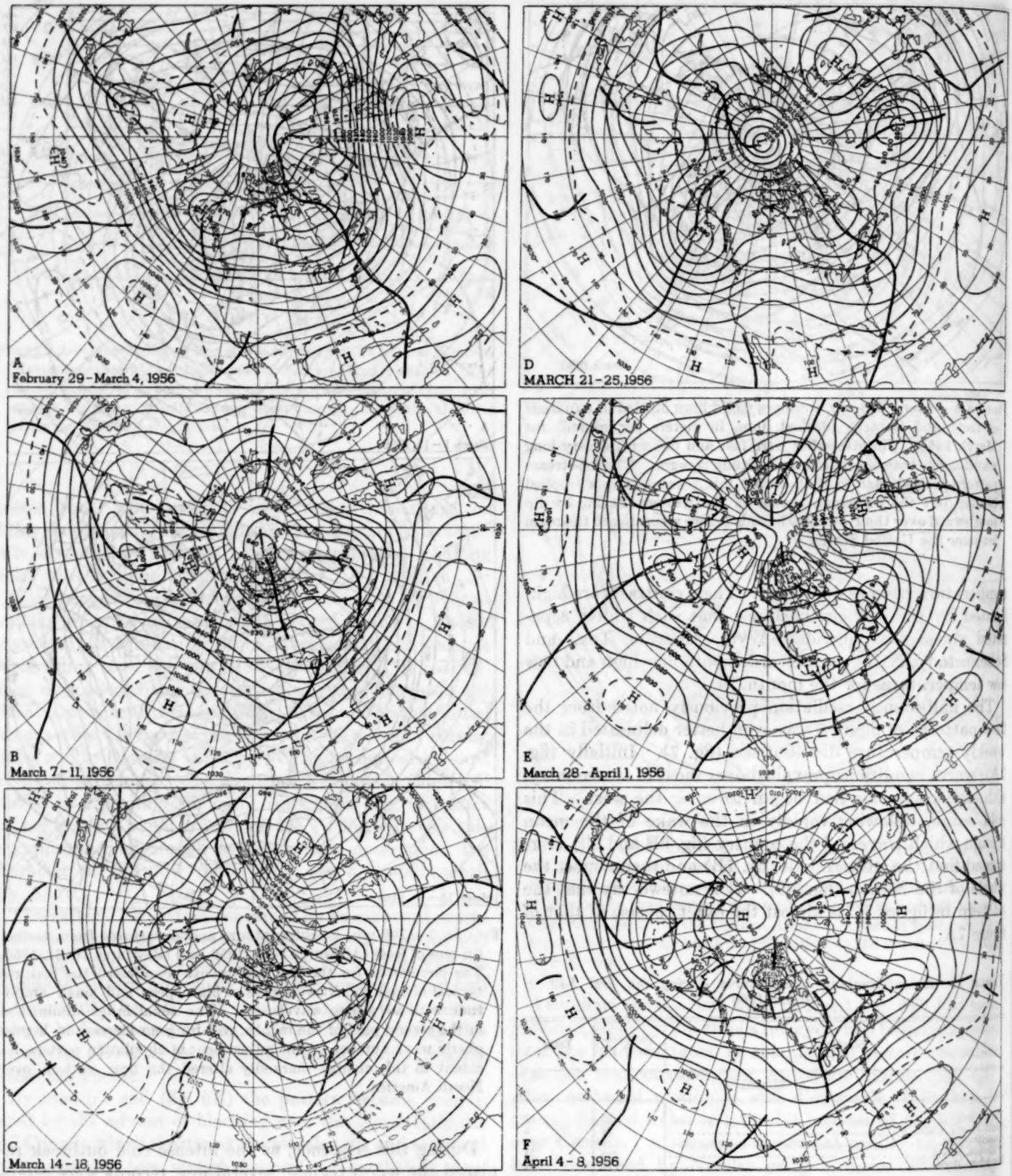

FIGURE 6.—5-day mean 700-mb. height contours in tens of feet for (A) February 24–March 4, (B) March 7–11, (C) March 14–18, (D) March 21–25, (E) March 28–April 1, and (F) April 4–8, 1956. As a consequence of fast westerly flow at middle latitudes in combination with the polar vortex, most features of 5-day mean charts progressed steadily eastward. This brought about a remarkable oscillation with reversal in pattern every second week.

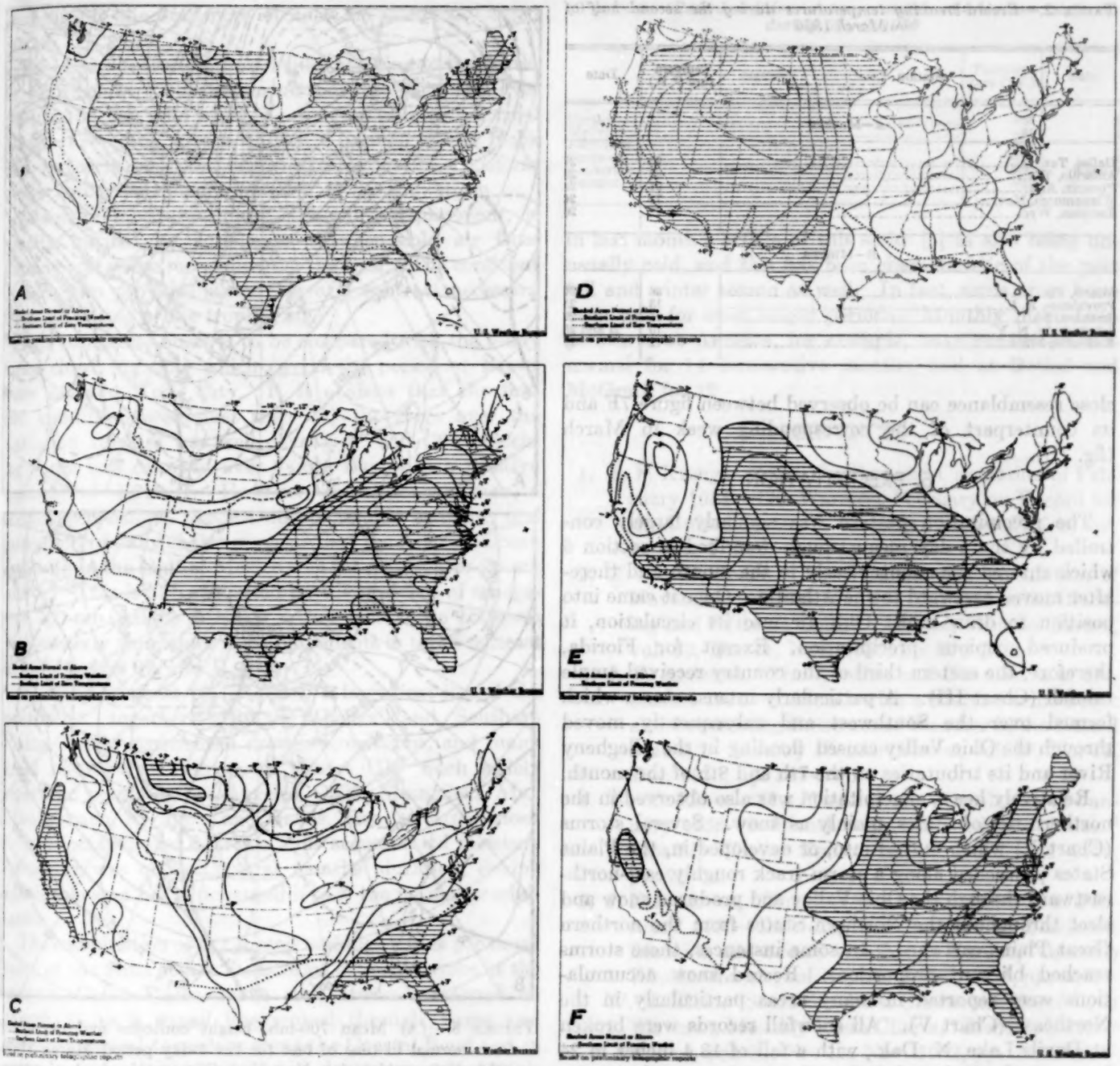

FIGURE 7.—Departure of average temperature from normal for the weeks ending at midnight local time (A) March 4, (B) March 11, (C) March 18, (D) March 25, (E) April 1, and (F) April 8, 1956. The cold air which had just entered the Pacific States the first week of the month marched steadily eastward until it overlay most of the country by the week ending March 19. By that time, however, above normal temperatures had begun to appear in Montana and along the west coast. This mild surge in turn moved east to overspread the western half of the country the following week (ending March 25). This then moved eastward and was replaced in the West once more by a new outbreak of cold air. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIII, Nos. 10 through 15, March 5 through April 9, 1956.)

air in turn continued eastward, until by month's end mild weather occupied a wide area embracing most of the central and southern States (fig. 7E). By this time a full cycle had been completed since this pattern was very similar to that at the beginning of the month (fig. 7A). Again new temperature records were established, but this time in an opposite sense. To permit comparison, a few instances have been listed in table 2.

The oscillation described above was not confined to March, but continued into the first part of April. The warm weather advanced to the eastern half of the country, and cold air reoccupied the West (fig. 7F). Once again a

TABLE 2.—*Record-breaking temperatures during the second half of March 1956*

Station	Temperature (° F.)	Date
A—Maxima		
Dallas, Tex.	95	27
Amarillo, Tex.	86	26
Phoenix, Ariz.	91	24
Winnemucca, Nev.	75	24
Sheridan, Wyo.	72	26
B—Minima		
Miami, Fla.	56	21
Providence, R. I.	13	25
Scranton, Pa.	11	21
Schenectady, N. Y.	10	21 and 25
Rochester, Minn.	−12	15

close resemblance can be observed between figure 7F and its counterpart of the corresponding week in March (fig. 7B).

6. PRECIPITATION

The precipitation pattern was similarly largely controlled by the 5-day mean trough described in section 5 which entered the country early in the month and thereafter moved eastward to the Atlantic. Once it came into position to draw moist Gulf air into its circulation, it produced copious precipitation. Except for Florida, therefore, the eastern third of the country received ample rainfall (Chart III). A particularly intense storm which formed over the Southwest and subsequently moved through the Ohio Valley caused flooding in the Allegheny River and its tributaries on the 7th and 8th of the month.

Relatively heavy precipitation was also observed in the northern tier of States, mainly as snow. Several storms (Chart X) which moved into, or developed in, the Plains States proceeded along a storm track roughly east-northeastward through the Ohio Valley and produced snow and sleet throughout the Northern States from the northern Great Plains eastward. In some instances, these storms reached blizzard proportions. Record snow accumulations were reported in many areas particularly in the Northeast (Chart V). All snowfall records were broken at Devils Lake, N. Dak., with a fall of 13.4 inches in 24 hours on the 27th and 28th and a total accumulation for the month of 25.6 inches. Numerous stations throughout the mountain regions of the Northeast reported the snowiest March on record, and New York City, with a total fall of 20.6 inches, suffered its heaviest snowfall since 1919. The snowstorm of March 16–17 has been briefly described by Sable [8] and Pack [9], but the most crippling storm occurred March 18–19 when a total of 13.5 inches of snow descended on New York City. A detailed treatment of the latter storm by Mook and Norquest begins on p. 116 of this issue.

In an attempt to isolate the meteorological factors contributing to snow at New York City, a composite chart was prepared comprising 10 5-day mean 700-mb. charts when snowfalls exceeding 5 inches occurred. This chart,

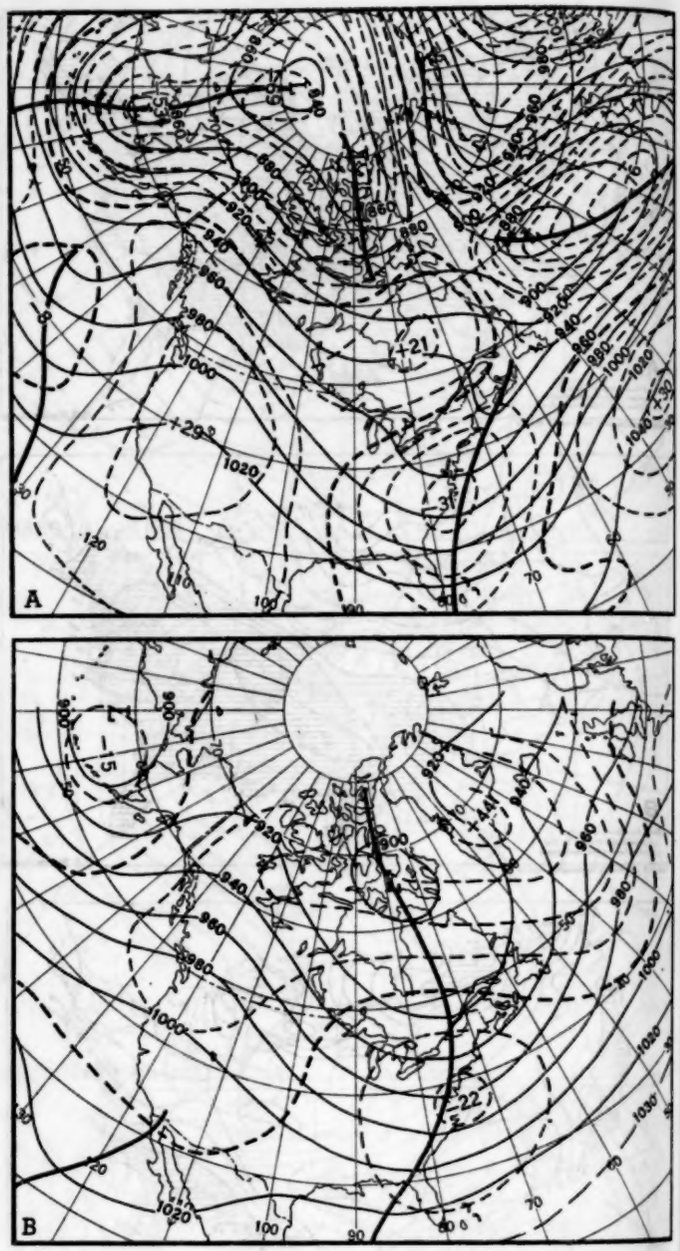

FIGURE 8.—(A) Mean 700-mb. height contours and departures from normal in tens of feet for the 5-day period March 17–21, 1956, during which time New York City sustained a heavy snowfall. (B) Composite mean 700-mb. height contours and departures from normal (tens of feet) for 10 5-day periods from 1947 to the present when snowfalls with accumulations greater than 5 inches occurred at New York City.

shown in figure 8B, closely resembles a composite chart prepared by Klein [10] for all daily 700-mb. maps with 1 inch or more of snowfall at Washington, D. C., since 1945. It illustrates the features listed by him and Namias [10] as being essential to snowstorm development in the Northeast: (1) The advection of cold air, (2) maintenance of cold air, (3) a mechanism for supply of warm moist air.

The first requirement is met (fig. 8B) by the existence of a large ridge in northwestern Canada to provide the

gradient for the transport of cold air into the United States.

The second feature is provided by blocking to the north, as evidenced by the center of positive anomaly over Greenland (fig. 8B) and the tongue of above-normal heights extending across northern Canada. The block also serves to slow the eastward progress of the storm center and permit longer duration of the snowstorm.

Adequate moisture supply, the third requirement, is usually insured by confluence between cold air from Canada and warm moist air from the Gulf. The confluent pattern also provides a sharp frontal contrast necessary for rapid lifting of the tropical air.

This composite chart is to be compared with the 5-day mean chart (fig. 8A) which covers the period of heavy snow at New York City. It is evident that the first two conditions were met since (1) the ridge over the Canadian Rockies was well developed, and (2) a blocking surge was centered over James Bay with a positive anomaly of +210 ft. However, the third condition, a confluence pattern, did not obtain in this instance, and inspection of daily charts suggests that the Atlantic Ocean rather than the Gulf of Mexico was the principal moisture source. This is also suggested by the presence of a negative 700-mb. height anomaly center near Cape Hatteras with easterly anomalous flow components in the Northeast in both figures 8A and B.

In sharp contrast to the East, a large fraction of the Southwest, together with the Central and Southern Plains States, experienced drought conditions, and many areas received no rain at all (Chart II). Such widely separated points as Los Angeles, Calif., Springfield, Mo., Albuquerque, N. Mex., and Dallas, Tex., all experienced their driest recorded March. This accumulated moisture deficiency was one of several months' duration, during which this area has experienced ¼ to ½ the normal precipitation.

The combination of dry topsoil and high winds produced some of the most severe duststorms of recent years in the western Great Plains. One such storm developed on March 21 as a squall line moved through Texas and triggered several tornadoes along the Coastal Bend and in central areas. A particularly bad duststorm entered this area again on March 27–28.

7. ALASKAN COLD

There remains one additional consequence of the polar vortex to discuss. The anomalous northerly flow to the west of this center was rather strong and poured repeated surges of air from the Arctic icecap into Alaska and northwestern Canada. This was particularly true of the first half of the month, when all of Alaska suffered cold of unusual severity. Numerous alltime records for March minima were established and a few have been listed in table 3.

Unseasonably cold weather has persisted in Alaska for a remarkably long period. February 1956 was reported in last month's article of this series [5] as also being unusually cold, and this has been characteristic of the past fall and winter season as well. In fact, some areas have been cold for even longer periods. Monthly mean temperatures at Annette, for example, have continued subnormal for 14 consecutive months, and at Bethel and McGrath for 12.

TABLE 3.—*Record minimum temperatures at Alaskan stations during March 1956*

Station	Temperature (° F.)	Date
Northway	−56	2
McGrath	−51	2
Fairbanks	−49	1
Cordova	−24	3
Anchorage	−22	5 and 9
Yakutat	−13	3

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THE HEAVY SNOWSTORM OF MARCH 18-19, 1956

The Climax of a Record Late-Season Snow Accumulation in Southern New England

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1. INTRODUCTION

The month of March 1956 was characterized by a series of late-season heavy snowstorms along the northeastern Atlantic coast of the United States. This report presents the results of a study of the meteorological conditions leading up to and attending the record-breaking snowstorm of March 18 and 19. This storm was the last of a series and presented unusual features which contributed to the difficulty of the forecast problem. The two storms within the 6 days preceding are discussed briefly to show the typical pattern of development of many east-coast snowstorms, and thus to furnish a background to reveal the contrasting features found in the present study.

2. ANTECEDENT CONDITIONS

On Friday, March 16, 1956, by 1230 GMT the stage was set for the typical development of a coastal Low which gives heavy snow and high winds in the Northeast. The North Atlantic States had been flooded with cold air due to eastward passage of a 1032-mb. High from the Great Lakes region to Maine. Meanwhile, a wave, which developed in the West Gulf on the trailing polar front, had deepened and moved northeastward to eastern Kentucky. This was attended by widespread heavy rains in the Southeastern States and snow through the Ohio Valley eastward to southern New Jersey. By this time the typical pattern of development was evident. A warm front lay along the Carolina coast, then extended eastward north of Bermuda. An area of 3-hourly pressure falls, of 4 to 5 mb. concentrated in eastern North Carolina and southeastern Virginia, strongly indicated a secondary development on the coast [5]. By 0030 GMT, March 17, 12 hours later, the low center in eastern Kentucky had entirely filled and the secondary Low had formed and deepened to 984 mb. just off Atlantic City, N. J. The pressure at Atlantic City fell 25 mb. in just 12 hours, indicating the explosive nature of the cyclogenesis which took place. Snow had now spread over all of the North Atlantic States, attended by strong winds with gales on the coast. By 0630 GMT, March 17, the center was 970 mb. just east of Nantucket. Snow and strong winds covered the Northeastern States and gales continued on the New England coast. By 1230 GMT, March 17, the storm was well out to sea some 380 miles east of Boston.

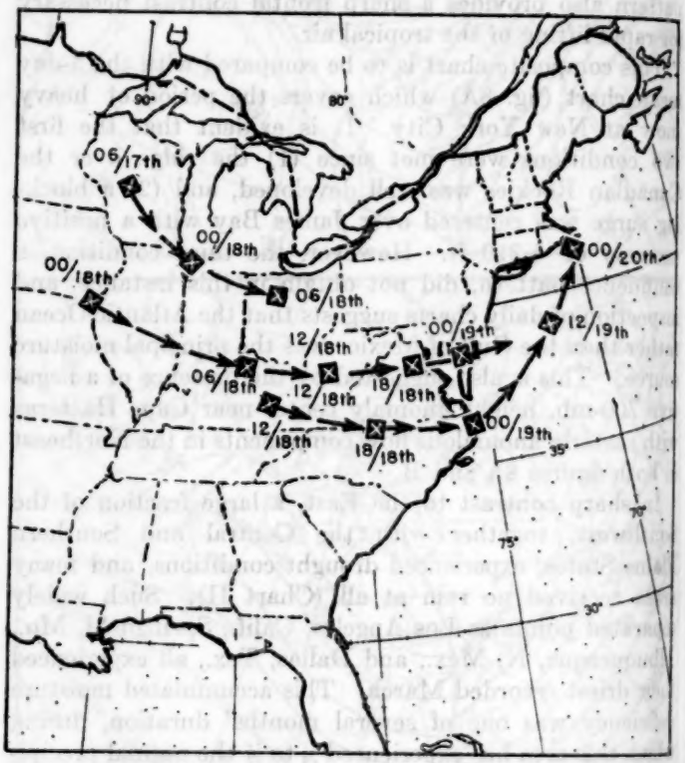

FIGURE 1.—Detailed track of Low associated with snowstorm of March 18–19, 1956.

This storm was a nearly perfect example of the rapid development of a coastal storm wherein high-level divergence is suddenly superimposed over a noncompensating warm sector in the manner described by Petterssen et al. [8]. It deposited 14 inches of new snow for a total depth of 20 inches at Albany, N. Y. It added 6 inches for a total of 10 inches at Hartford, Conn., and 10 inches for a total depth of 24 inches at Concord, N. H. New York City and Boston, Mass., were left with 5 and 7 inches of new snow, respectively.

It is important to note that this storm moved at a rate of 43 knots, passing just south of Nantucket. In 12 hours it moved from a position off the coast near Atlantic City to 380 miles east of Boston.

A similar but less explosive example occurred just 2 days previously, on March 14, 1956. This was the first of the series of three snowstorms which visited New York and

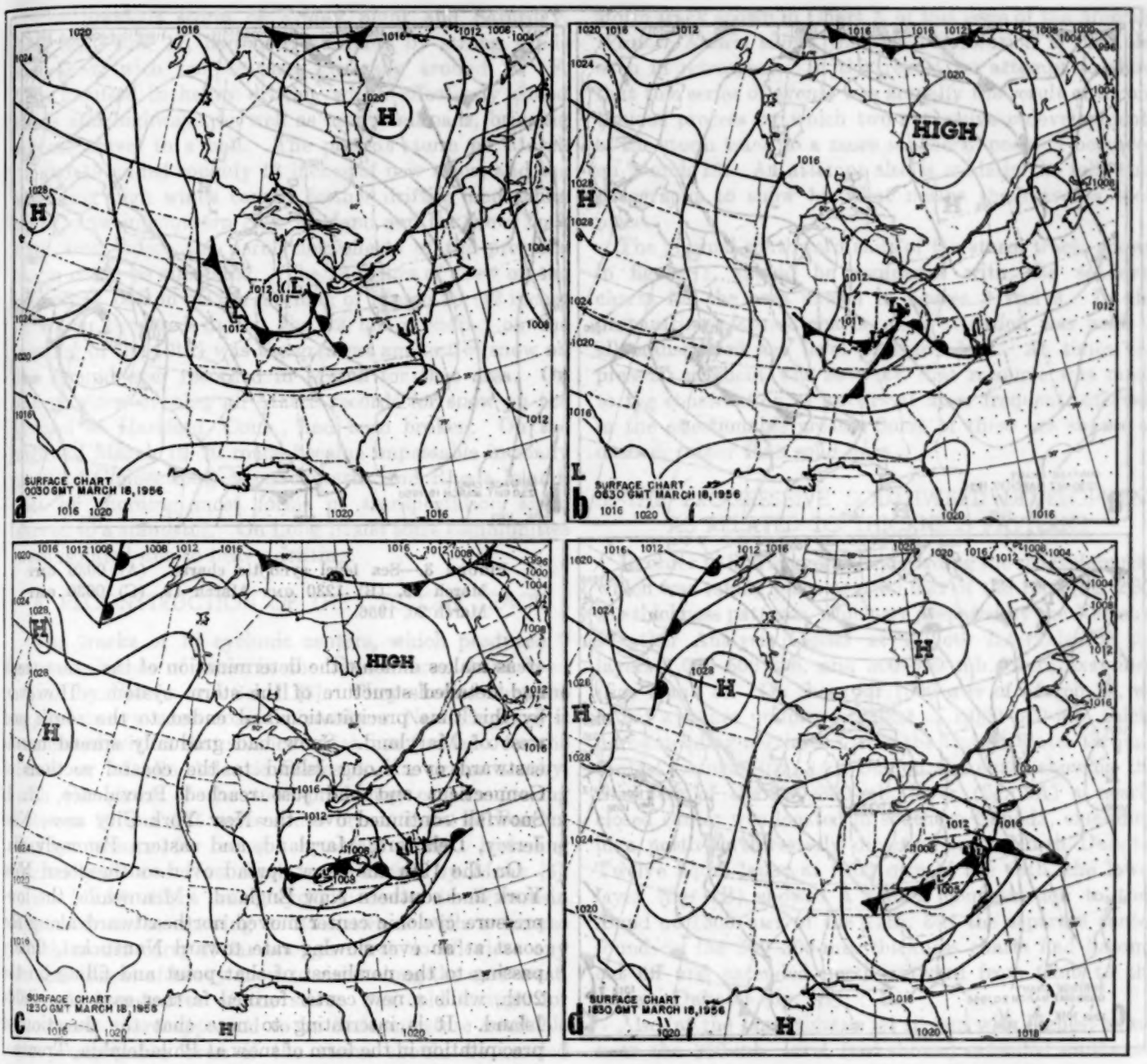

FIGURE 2.—Sea level synoptic charts for March 18, 1956. (A) 0030 GMT, (B) 0630 GMT, (C) 1230 GMT, (D) 1830 GMT.

New England in 6 days. The first two were typical developments which meteorologists have learned to handle fairly well. The third of the series was unusual and is the subject of this paper.

3. CHARACTERISTICS OF THE SNOW OF MARCH 18–19

By early morning of the 18th (1230 GMT) the area of snowfall attending the developing southern low centers over eastern Kentucky and southern West Virginia (fig. 2C) had enlarged to cover the Ohio Valley and had spread eastward over the Appalachians to cover Pennsylvania, southern New Jersey, Maryland west of Chesapeake Bay, and western and northern Virginia. Measurable amounts of snow had fallen only as far east as Harrisburg, Pa., and the Roanoke-Lynchburg area of Virginia.

By early afternoon of the 18th, 1830 GMT, (fig. 2D), precipitation covered the Middle Atlantic States from New York City to Norfolk, Va., and extended westward through West Virginia to Cincinnati, Ohio. Precipitation fell as rain over southern Maryland and southern Virginia, while snow was falling over the remainder. Snow had spread from southern New Jersey, beginning at 1545 GMT at Newark and 1603 GMT at New York City. At this time one low center was moving eastward near

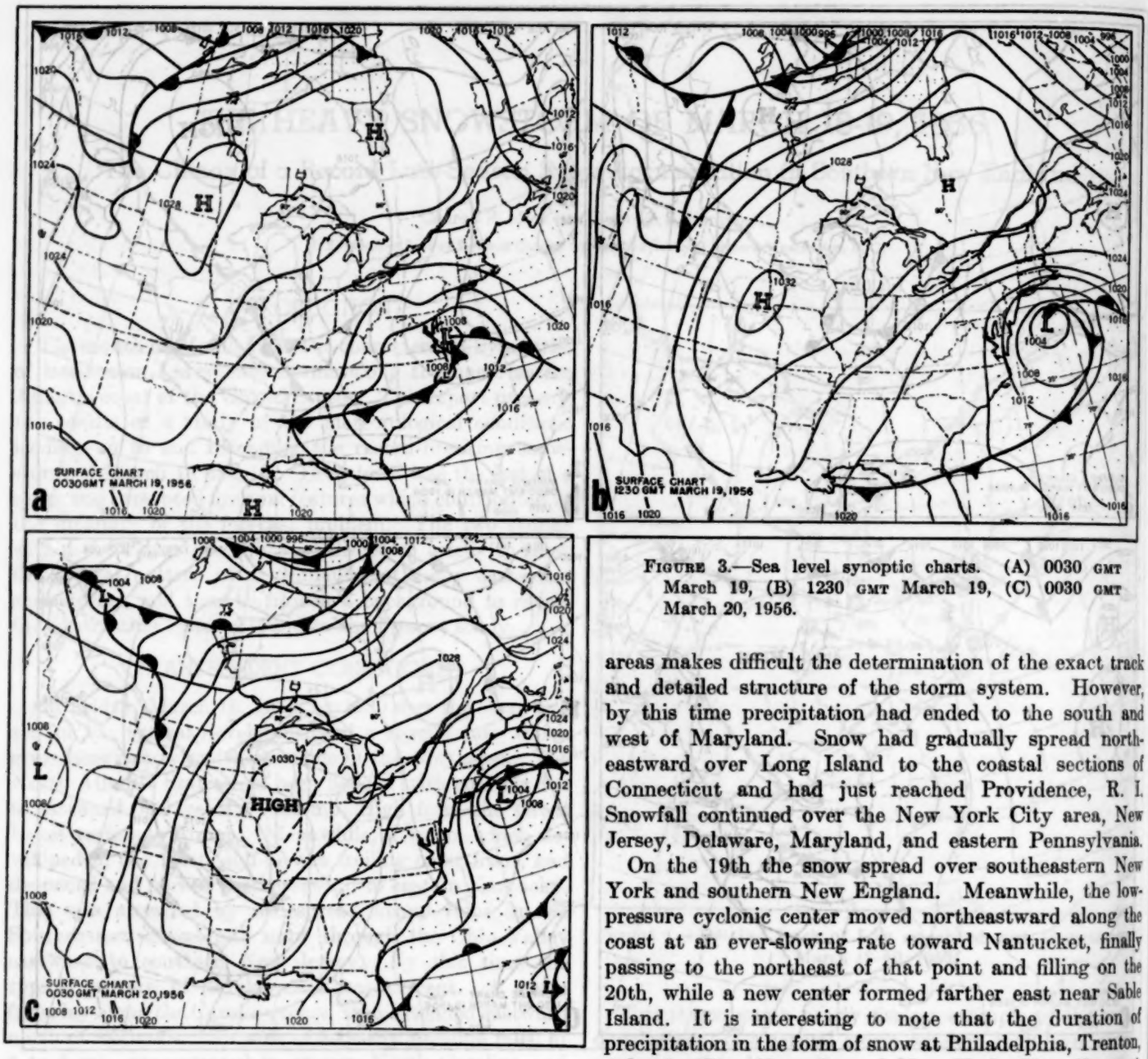

FIGURE 3.—Sea level synoptic charts. (A) 0030 GMT March 19, (B) 1230 GMT March 19, (C) 0030 GMT March 20, 1956.

Quantico, Va., while another was also moving eastward near Danville, Va.

During the next 6 hours there was little change in the area of precipitation. Showers and thunderstorms moved eastward across southern Virginia and eastern North Carolina as the southern low center moved to the coast near Elizabeth City, N. C., by 0030 GMT (fig. 3A). Snow continued from Maryland and Delaware northward over Pennsylvania and into Long Island as well as westward to Cincinnati, Ohio, as the northern low center moved to southern Delaware.

By 0630 GMT of the 19th (see fig. 3B for 1230 GMT) the surface low system was off the coast, some distance southeast of New Jersey, moving northeastward. Lack of receipt of a sufficient number of reports over the water areas makes difficult the determination of the exact track and detailed structure of the storm system. However, by this time precipitation had ended to the south and west of Maryland. Snow had gradually spread northeastward over Long Island to the coastal sections of Connecticut and had just reached Providence, R. I. Snowfall continued over the New York City area, New Jersey, Delaware, Maryland, and eastern Pennsylvania.

On the 19th the snow spread over southeastern New York and southern New England. Meanwhile, the low-pressure cyclonic center moved northeastward along the coast at an ever-slowing rate toward Nantucket, finally passing to the northeast of that point and filling on the 20th, while a new center formed farther east near Sable Island. It is interesting to note that the duration of precipitation in the form of snow at Philadelphia, Trenton, Atlantic City, Newark, and New York City (Battery) ranged from 31 hours at Philadelphia to 35 hours at Atlantic City. Farther east, over southern New England, the duration ranged from 26 hours at New Haven to 24 hours at Boston. In spite of this, however, the depth of new snow added by the storm was remarkably uniform, measuring 12 to 13 inches at Trenton, New York City, New Haven, Bradley Field (Hartford), and Boston. A notable exception was the 18 inches which fell at Newark. There, for a 6-hour period, precipitation occurred at a rate of 0.14 inch per hour (melted). This was three times the hourly rate of 0.05 inch which prevailed for 10 hours prior to and 4 hours immediately following this period of heaviest snow. It is curious to note that at Trenton a uniform rate of around 0.05 inch (melted) was maintained for 20 hours.

The previous storm of Friday night and Saturday, March 16 and 17, had been attended by strong winds and snow with temperatures generally around 20° F. This resulted in heavy drifting which effectively closed roads and highways, as well as many railroads, bringing surface travel to a halt. The present storm on March 18 and 19 added roughly 13 inches of new snow, and the attending high winds caused further drifting and piling up of snow in southern New England and the New York City area before the paralyzing effects of the previous storm could be alleviated. The 18 inches of snow on the ground at Boston on the morning of March 20 (12 inches of which occurred during the 12 hours ending on the evening of the 19th) was the greatest amount of snow on the ground ever recorded in March for that area. On the previous evening all March records for snow on the ground at Hartford, Conn., had been broken. On the night of March 19–20 roads became impassable in many parts of Connecticut, Massachusetts, and Rhode Island, and by morning most forms of transportation again slowed to a standstill. On Long Island some communities were isolated due to heavy drifting.

4. RECONSTRUCTION OF THE CYCLONE TRACK

The tracks of 16 cyclonic centers, which produced 9 or more inches of snow in the Boston area, have been shown by Brooks and Schell [3]. They showed that the typical heavy snowstorm in southern New England is associated with a disturbance which has formed over the South or Middle Atlantic States or the ocean nearby, with the paths of the snow-producing centers passing between 70 and 265 miles south or southeast of Boston. Similar tracks for other east-coast cities, including Philadelphia and New York, were shown by Mook [6].

On March 17, a weak cyclonic center in Wisconsin appeared to be moving southeastward with a course which would carry it far enough north to alleviate any further threat of heavy snow to cities along the east coast. The air in advance of the storm was cold enough for snow, but there appeared to be little moisture available for precipitation even if the storm should be carried southward. An example of the purely objective indications presented by this storm may be found in the 1,000-mb. prognostic charts prepared on an electronic computer by the Joint Numerical Weather Prediction Unit, using a quasi-geostrophic, 3-parameter model and data from 1500 GMT on March 17. By this method one would have expected the Low to be located just northwest of Toledo, Ohio, at 1500 GMT of the 18th and in northwestern Pennsylvania at 0300 GMT of the 19th. Actually, by 0300 GMT of the 19th, heavy snow had already occurred in southeastern Pennsylvania from a developing system off the coast east of Virginia. (See fig. 1.)

At the time of this development it appeared that the Wisconsin Low had suddenly plunged southward after reaching Ohio early on March 18, thereafter following an eastward course through Virginia during the day. The storm track shown in Chart X of this issue of the *Monthly Weather Review* shows that such a solution is possible, even in retrospect. In this report we attempt to show that this series of events was actually the result of a continuous process by which two successive redevelopments of the storm track to a more southerly position occurred on March 18. An attempt also is made in the following paragraphs to show by what means these events took place.

The gradual southward shift of the storm track, shown in figure 1, should be compared with the sea-level charts for the area shown in figures 2 and 3. In the preparation of these charts, close attention was paid to all transmitted sea level pressure data. At times the pressure gradient was so weak that recourse was made to the construction of isobars at more frequent intervals in the questionable areas. Some of these are shown as dashed, rather than solid lines.

5. THE PROGRESSIVE SOUTHWARD DEVELOPMENT AS RELATED TO THICKNESS PATTERNS

In order to find suggestions regarding the redevelopment which was taking place at 0630 GMT of the 18th (fig. 2B), the thickness patterns, which are prepared by the National Weather Analysis Center at 12-hour intervals for the layers 1,000–500 mb. and 500–300 mb., were examined (figs 4 and 5). On those for 1500 GMT of March 17, we found a rather uniform gradient of 1,000–500-mb. thickness extending northward from the United States through central Canada (fig. 4A), but on the chart showing the thickness of the 500–300-mb. layer (fig. 5A) a nearly closed center was located in southern Canada, extending in a north-northwesterly direction from North Dakota. Twelve hours later, at 0300 GMT of the 18th, the lower layer (fig. 4B) showed a similar configuration to that found at 1500 GMT of the 17th, but the separate center found on the 500–300-mb. thickness charts had become cut off and extended northwestward from Ohio to the eastern Dakotas (fig. 5B).

Also, at the same time, a jet stream with highest winds near the 300-mb. level (not shown) extended southeastward from Montana to South Carolina with a jet maximum, containing winds of greater than 150 knots, lying across central Missouri parallel to the high-level cold air "island", represented by the closed center on the 500–300-mb. thickness chart (fig. 5B). Note here, however, that the developing sea level cyclone, moving eastward through southern Illinois and Indiana, was not located beneath the jet stream, but rather *its track lay beneath the southern boundary of the closed center on the 500–300-mb. thickness chart.* This observation, therefore, leads us to suggest the following hypothesis regarding the redevelopment of the cyclone farther to the south, between 0030 and 0630 GMT of March 18.

The weather accompanying the northern center had, up until this time, been characterized by small amounts of snowfall and, therefore, presumably relatively low vertical

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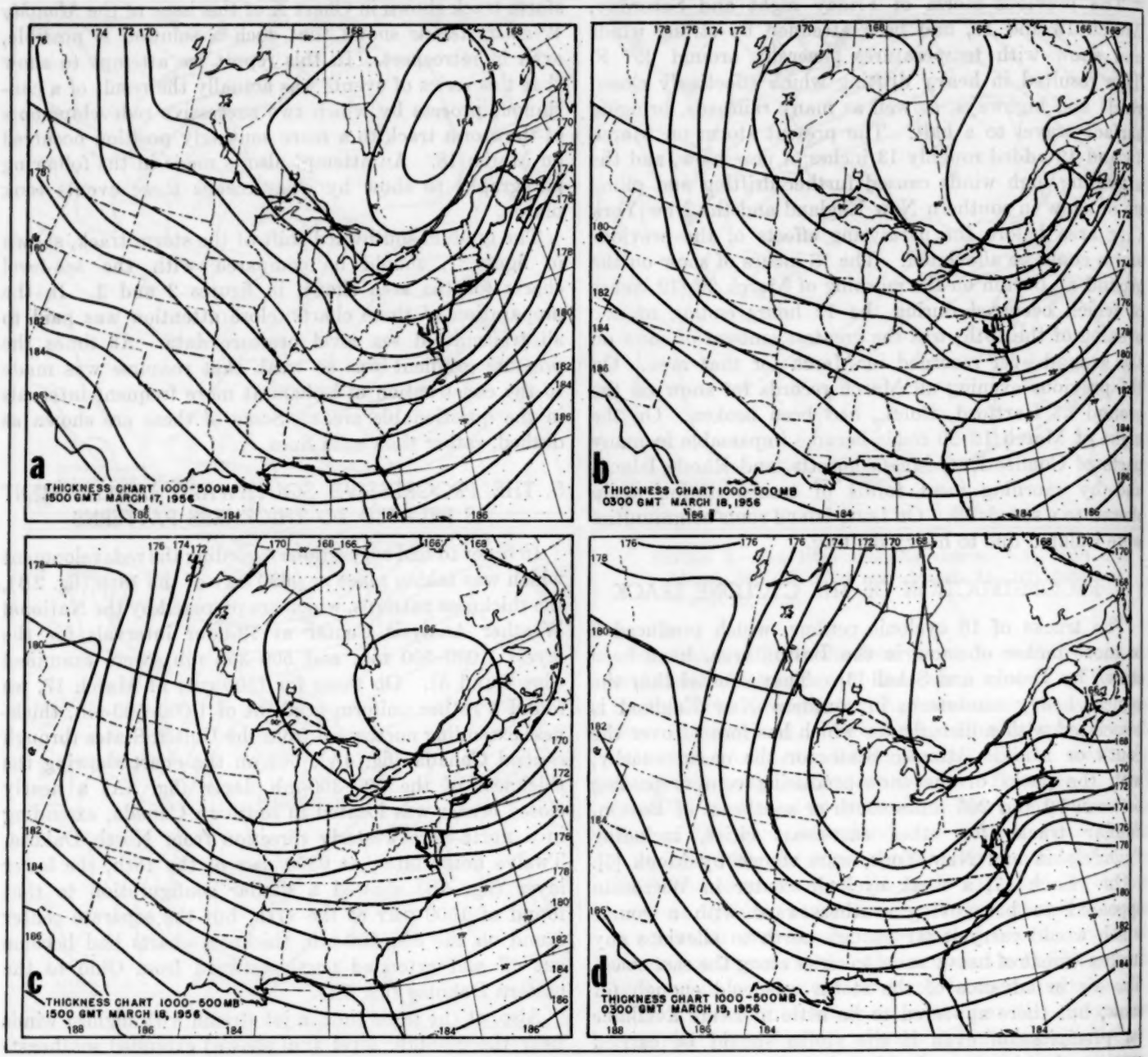

FIGURE 4.—1,000–500-mb. thickness patterns. (A) 1500 GMT, March 17, (B) 0300 GMT, March 18, (C) 1500 GMT, March 18, (D) 0300 GMT, March 19, 1956.

motion speeds. The snow persisted in the wake of the storm path suggesting that there was some lag in the precipitation processes as compared with the movement of the Low. The appearance of the cutoff cold air center over this snow pattern, even though the amounts of snow were small, suggests that this center may have developed, or have been maintained at least in part, by cooling produced by upward vertical air motions. If this is true, we have at hand a mechanism for producing a considerable amount of lateral shear (or vorticity) over the region of new development. The mechanism envisaged here is associated with the often-neglected "twisting" term in the vorticity equation, wherein relatively high-speed air can be transported downward, and conversely, relatively low-speed air can be transported upward.

The role of this term can be seen in the complete vorticity equation wherein it is the second term on the right:

$$\frac{d\eta}{dt}=-\eta\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)-\left(\frac{\partial \dot{p}}{\partial x}\frac{\partial v}{\partial p}-\frac{\partial \dot{p}}{\partial y}\frac{\partial u}{\partial p}\right)$$

where p is the vertical coordinate,

$\frac{d\eta}{dt}$=time rate of change of absolute vorticity

$\dot{p}=\frac{dp}{dt}$, an approximate measure of vertical motion.

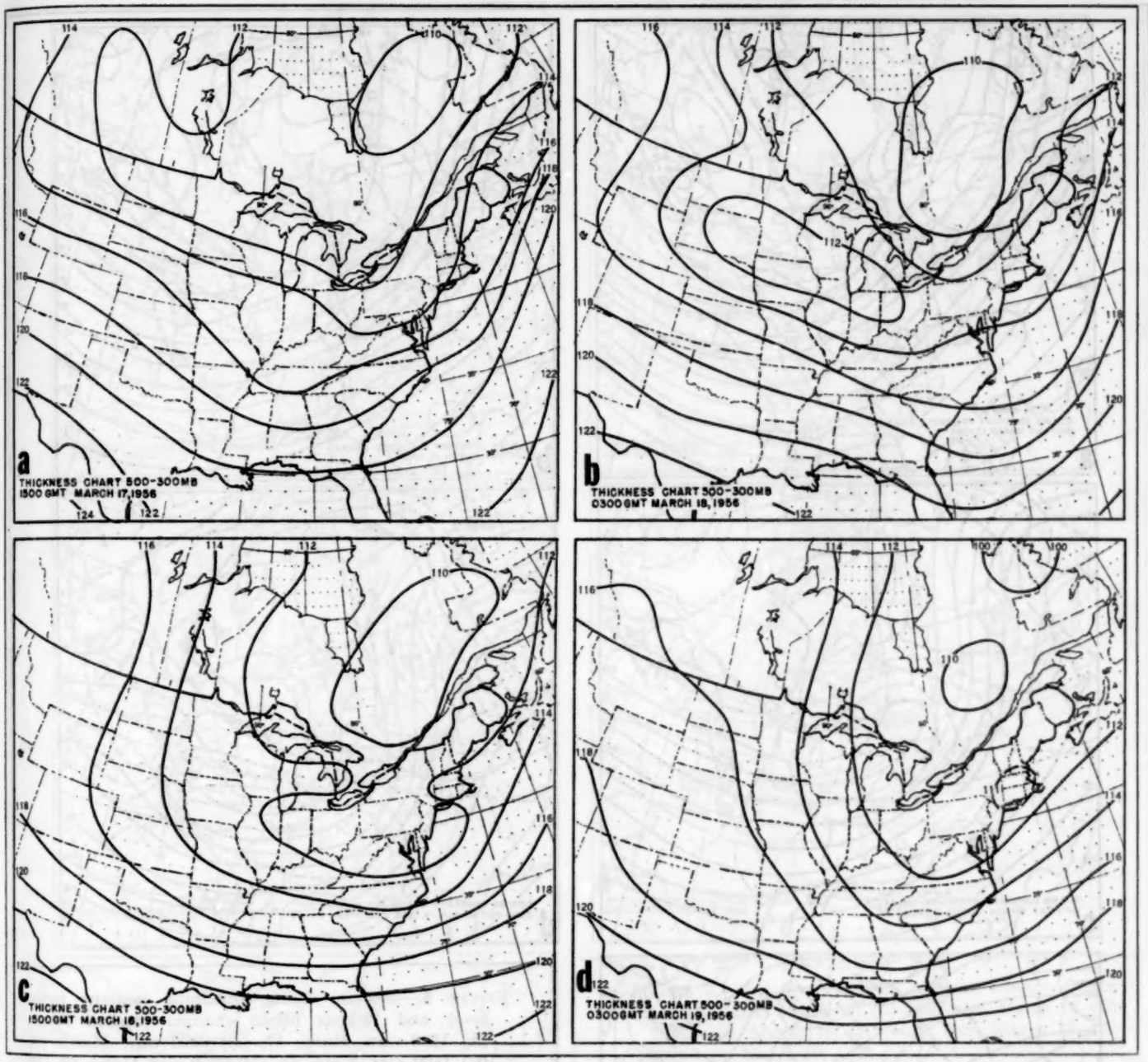

FIGURE 5.—500–300-mb. thickness patterns. (A) 1500 GMT, March 17, (B) 0300 GMT, March 18, (C) 1500 GMT, March 18, (D) 0300 GMT, March 19, 1956.

Though usually neglected, the twisting term may become important at levels where large-scale vertical motions reach a maximum, such as near the level of nondivergence.

Reed and Sanders [9] have applied a twisting term to the study of frontogenesis in the mid-troposphere, and Austin [2] has proclaimed its usefulness in the prediction of trough development at the 500-mb. level in circumstances where the upper-level temperature fields give evidence of its possible application.

A comparison of subsequent 500–300-mb. thickness charts (fig. 5B, C, D) with the storm track (fig. 1) indicates how the Low remained coupled with the southern edge of the cold center. During this period the jet stream continued well south and southeast of the cyclone center, a situation which Vederman [7] found to exist in only 1 out of 5 Boston snowstorms which he examined.

6. COMPARISON OF THE ROLES OF HIGH-LEVEL DIVERGENCE AND LOW-LEVEL TEMPERATURE ADVECTION IN THE INTENSIFICATION OF THE CYCLONE

At 1500 GMT on March 17, the 12-hour height changes at 500 mb. showed a closed center of falls over eastern Montana and western North Dakota (fig. 6A). The corre-

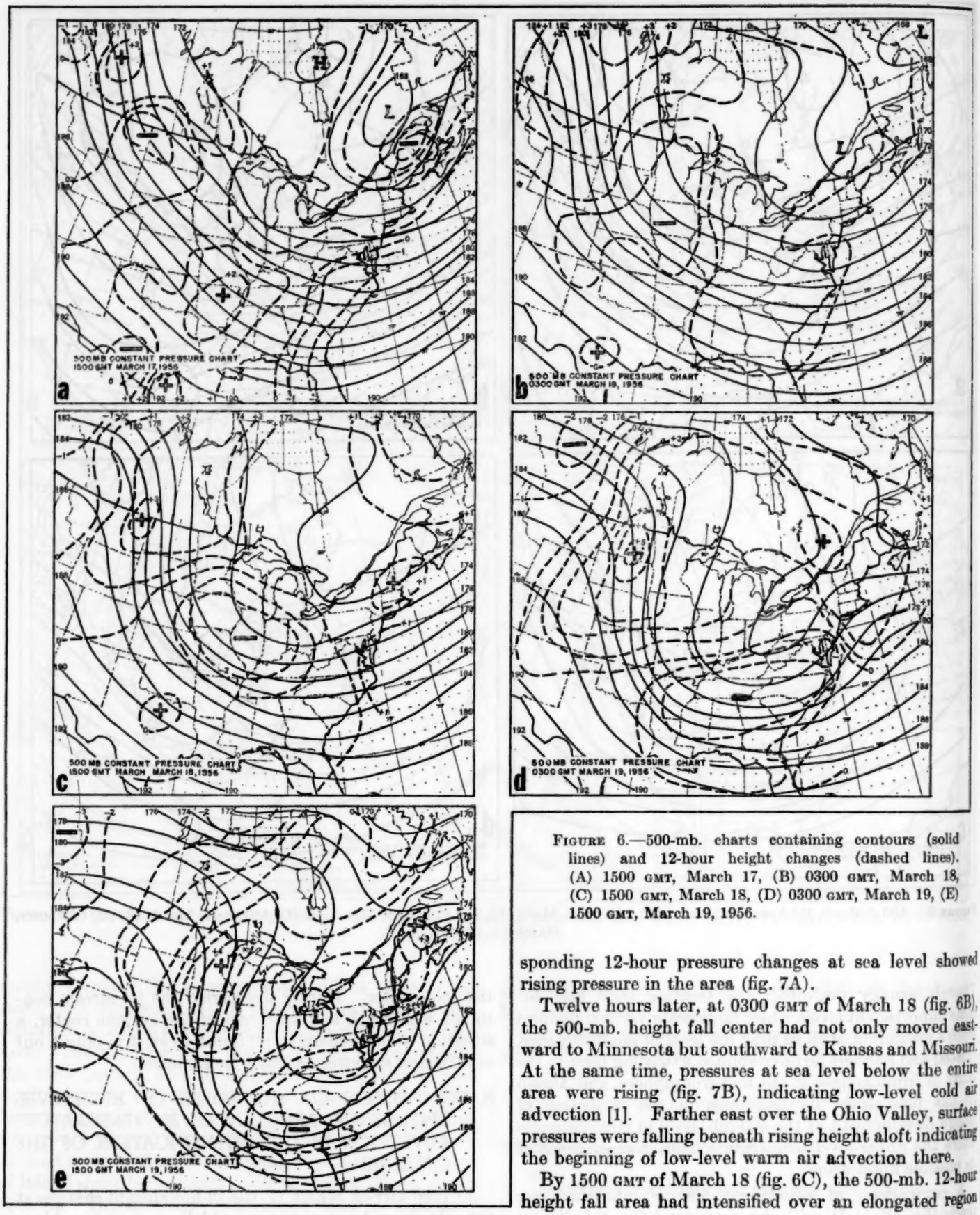

FIGURE 6.—500-mb. charts containing contours (solid lines) and 12-hour height changes (dashed lines). (A) 1500 GMT, March 17, (B) 0300 GMT, March 18, (C) 1500 GMT, March 18, (D) 0300 GMT, March 19, (E) 1500 GMT, March 19, 1956.

sponding 12-hour pressure changes at sea level showed rising pressure in the area (fig. 7A).

Twelve hours later, at 0300 GMT of March 18 (fig. 6B), the 500-mb. height fall center had not only moved eastward to Minnesota but southward to Kansas and Missouri. At the same time, pressures at sea level below the entire area were rising (fig. 7B), indicating low-level cold air advection [1]. Farther east over the Ohio Valley, surface pressures were falling beneath rising height aloft indicating the beginning of low-level warm air advection there.

By 1500 GMT of March 18 (fig. 6C), the 500-mb. 12-hour height fall area had intensified over an elongated region

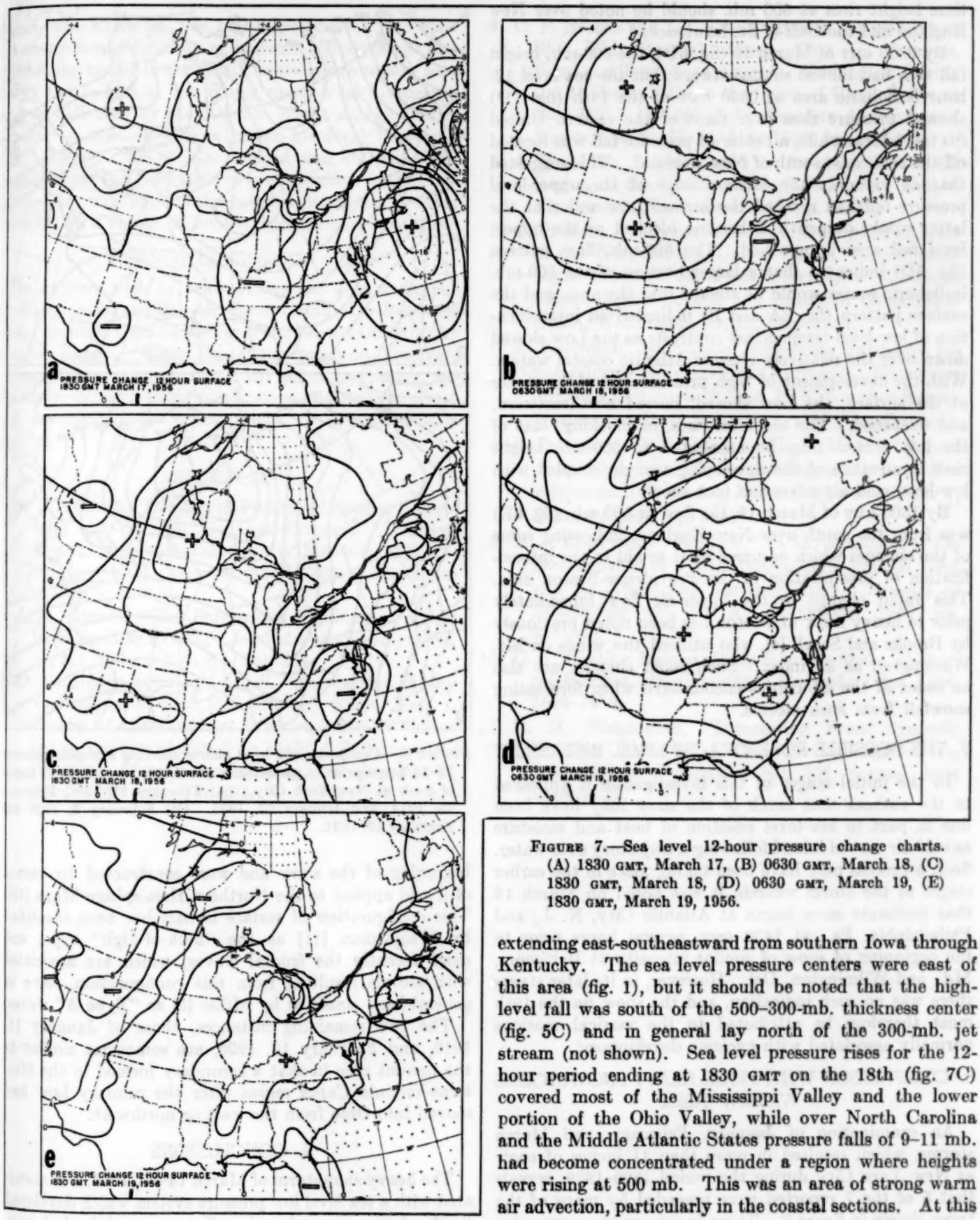

FIGURE 7.—Sea level 12-hour pressure change charts. (A) 1830 GMT, March 17, (B) 0630 GMT, March 18, (C) 1830 GMT, March 18, (D) 0630 GMT, March 19, (E) 1830 GMT, March 19, 1956.

extending east-southeastward from southern Iowa through Kentucky. The sea level pressure centers were east of this area (fig. 1), but it should be noted that the high-level fall was south of the 500–300-mb. thickness center (fig. 5C) and in general lay north of the 300-mb. jet stream (not shown). Sea level pressure rises for the 12-hour period ending at 1830 GMT on the 18th (fig. 7C) covered most of the Mississippi Valley and the lower portion of the Ohio Valley, while over North Carolina and the Middle Atlantic States pressure falls of 9–11 mb. had become concentrated under a region where heights were rising at 500 mb. This was an area of strong warm air advection, particularly in the coastal sections. At this

time height rises at 500 mb. should be noted over New England and the Gulf of St. Lawrence.

By 0300 GMT of March 19 (fig. 6D), the 500-mb. height fall area had moved southeastward, but the sea level 12-hour isallobaric area at 0630 GMT of the 19th (fig. 7D) showed pressure rises over most of the eastern United States. Meanwhile, a center of pressure fall was located off the east coast south of New England. This suggested that as yet only the forward edge of the upper-level pressure fall had reached the surface Low and that the latter would deepen if it became blocked as the upper-level fall area approached. The 500-mb. flow pattern (fig. 6D) indicated that a larger portion of the 500-mb. isallobaric center would be steered into the area, and the surface pattern (fig. 3A and B) indicated an intensification of low-level temperature contrasts as the Low slowed down over the relatively warmer Atlantic coastal waters. With the development of high pressure east of the center at the surface, the Low slowed, moved northeastward, and deepened. The sea level rises, or blocking, east of the low center, may be attributed to 500-mb. height rises in advance of the developing trough, coupled with low-level cold air advection (not shown).

By 1500 GMT of March 19, the flow at 500 mb. (fig. 6E) was from the south over New England, indicating some of the changes which occurred aloft to aid in the intensification of precipitation in the Providence-Boston area. This rapid change in the upper-air flow immediately prior to heavy snow at Boston has been noted previously by Brooks and Schell [4], who utilized the winds on Mt. Washington as an index. Such rapid changes are also an index of the difficulties encountered when forecasting snowfall from such storms.

7. THE POSSIBLE ROLE OF LOW-LEVEL INSTABILITY

In the initial stages of this investigation it appeared to the authors that much of the snow may have been due in part to low-level addition of heat and moisture as cold air moved inland following a trajectory over water. Such a process may have been taking place in the earlier stages of the storm wherein it was noted on March 18 that moderate snow began at Atlantic City, N. J., and Philadelphia, Pa., at 1430 GMT, several hours prior to the beginning of snow of similar intensity at Baltimore, Md., and Wilmington, Del. However, in its later stages there was no such indication, and the snow on the 19th must therefore be attributed to the vertical motions normally associated with cyclonic development.

8. COMPARISON WITH PRIOR HEAVY SNOWSTORMS AT NEW YORK

An examination of January, February, and March storms, which resulted in more than 11 inches of snow at New York City during the period 1899–1939, reveals that 5 of the 7 reported were preceded by maps of the types shown in figure 8. These two maps are composites of surface isobaric patterns 12 to 24 hours prior to the beginning of the snow and were constructed by means of a grid applied to the Northern Hemisphere Maps [10]. This configuration of surface isobars has been identified by Weightman [11] as the "neck-of-high" type, and more recently the frontal waves, which are associated with storms resulting from this configuration, have in general been classified by Miller [5] as "Type A" waves.

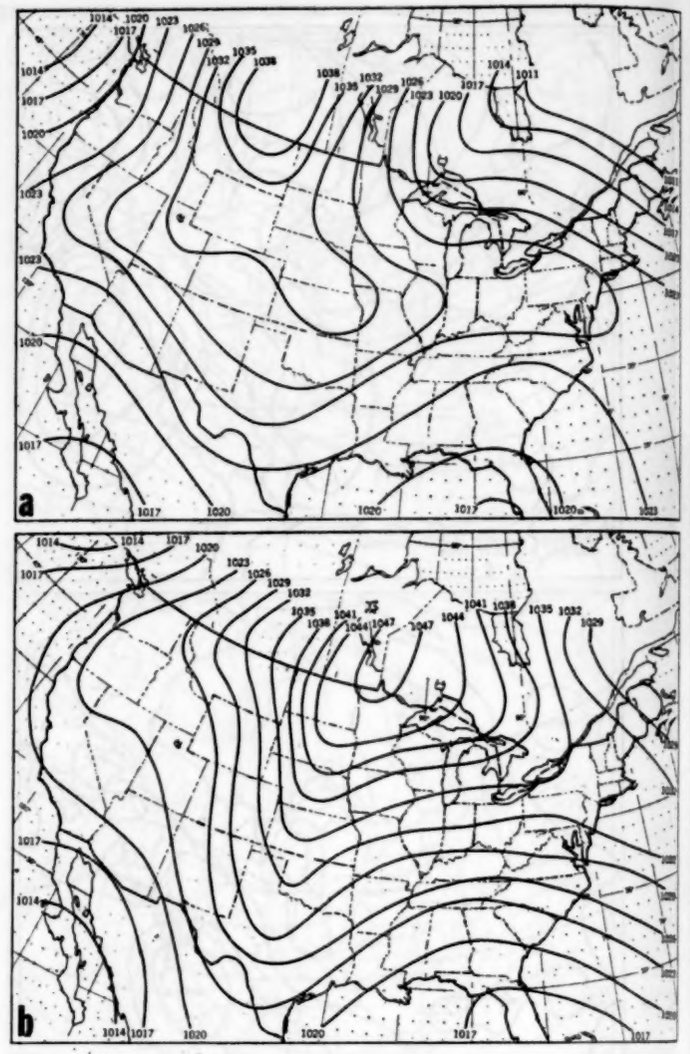

FIGURE 8.—Composite sea level charts showing synoptic patterns 12–24 hours prior to snowstorms producing more than 11 inches of snow at New York City. (A) February 11, 1899, February 28, 1914, and January 22, 1935. (B) February 3, 1920 and February 19, 1921.

The two remaining instances, those of January 15, 1910, and February 10, 1926, are somewhat similar to the present case in that a secondary formed in the Hatteras-Virginia Capes region after the primary Low had moved into Ohio from the west or northwest.

9. CONCLUSIONS

The heavy snowstorm of March 18–20, 1956, was associated with a sea level low pressure system which developed north of the zone of major divergence aloft, but in a zone where cyclonic vorticity generation and/or fronto-

genesis was likely in the mid-troposphere. The slow and erratic reestablishment of cyclonic activity southeast of the filling center in the Great Lakes region was in part due to the failure of the major upper-level divergence zone, as indicated by the 500-mb. height change center, to come in contact with a major low-level baroclinic zone. Instead, the cyclone formed and intensified in a region where the generation of cyclonic shear in the mid-troposphere was apparently coupled with the gradual *generation* of a region of low-level temperature contrast.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of Dr. David Atlas, of the Air Force Cambridge Research Center, and Mr. Charles Pierce, of the Boston Office of the Weather Bureau. Time limitations preclude, however, the acceptance at present of their offers to furnish, for this study, detailed radar information and its interpretation, concerning the precipitation in southern New England.

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3. C. F. Brooks and I. I. Schell, "Forecasting Heavy Snowstorms at Blue Hill (Boston), Mass. Part I. Tracks of the Cyclones Producing Heavy Snows in the Winters of 1938/9 to 1946/7," *Bulletin of the American Meteorological Society*, vol. 31, No. 4, April 1950, pp. 131–133.
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7. J. Vederman, Jet Stream Indications Favorable for Snowstorms, Notes on Staff Conference. Discussion of East Coast Snow Storms, U. S. Weather Bureau Washington, D. C. October 31, 1955 (Unpublished).
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9. R. J. Reed and F. Sanders, "An Investigation of the Development of a Mid-Tropospheric Frontal Zone and its Associated Vorticity Field," *Journal of Meteorology*, vol. 10, No. 5, October 1953, pp. 338–349.
10. U. S. Weather Bureau, *Daily Synoptic Series, Historical Weather Maps, Northern Hemisphere Sea Level*, 1899–1939.
11. R. H. Weightman, "Forecasting From Synoptic Weather Charts," U. S. Department of Agriculture, *Miscellaneous Publication* No. 236, revised June 1940, p. 35.

CORRECTION

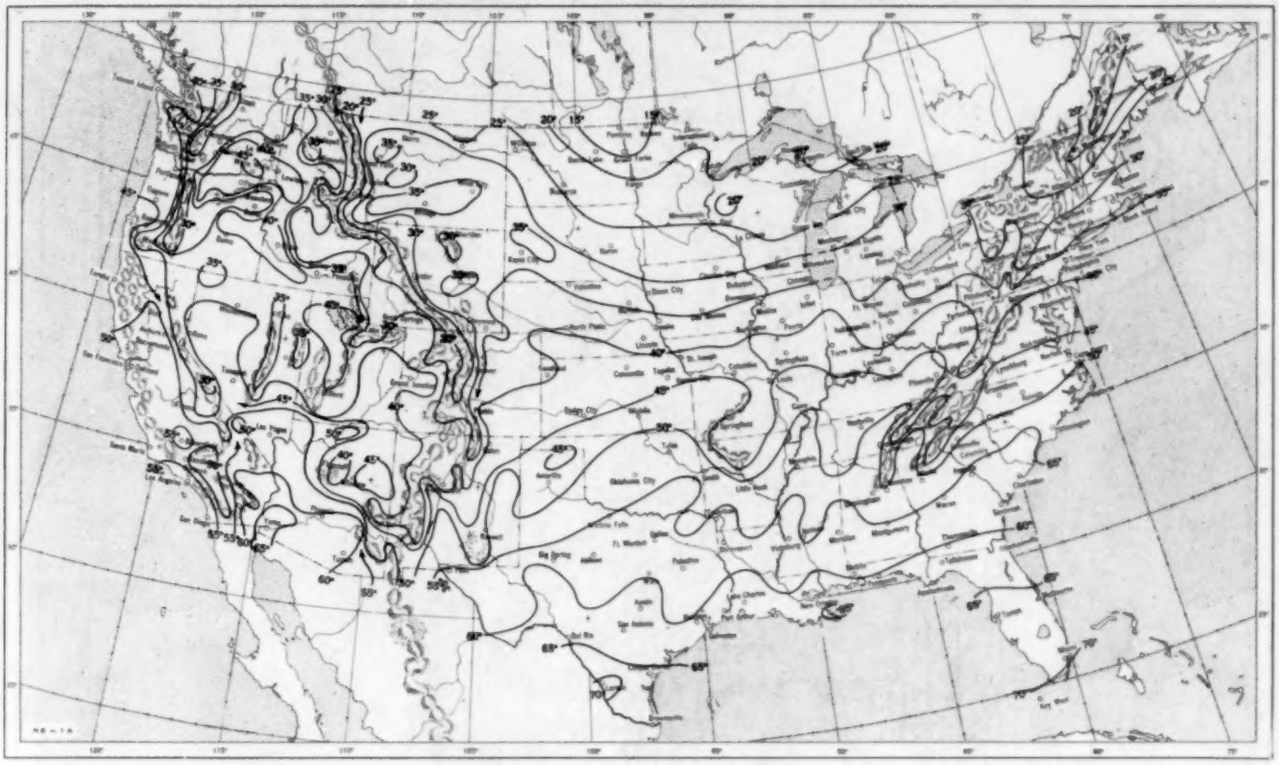
Charts IX and X, the anticyclone and cyclone tracks, for the months October 1955 through February 1956, and published in the issues for those months, are incorrectly registered with the blue base map. The error amounts to about 10° of latitude and up to 7°–8° of longitude in the extreme northwestern and northeastern corners of the map, and up to 35° of longitude in the central areas north of 65° N. In the center portions across the United States the error is small.

The tracks for March 1956 in this issue are correct.

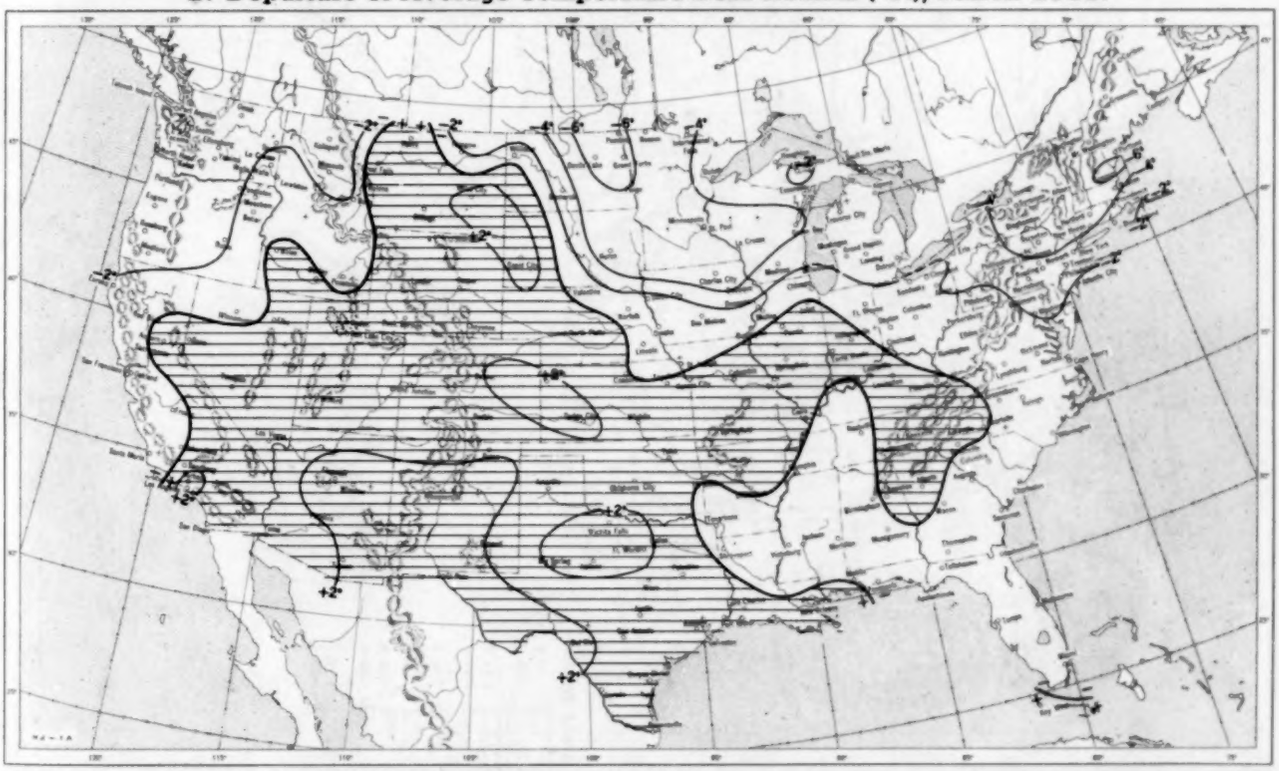
New corrected maps will be printed for October through February and forwarded to all subscribers in the near future.

U. S. GOVERNMENT PRINTING OFFICE: 1956

Chart I. A. Average Temperature (°F.) at Surface, March 1956.

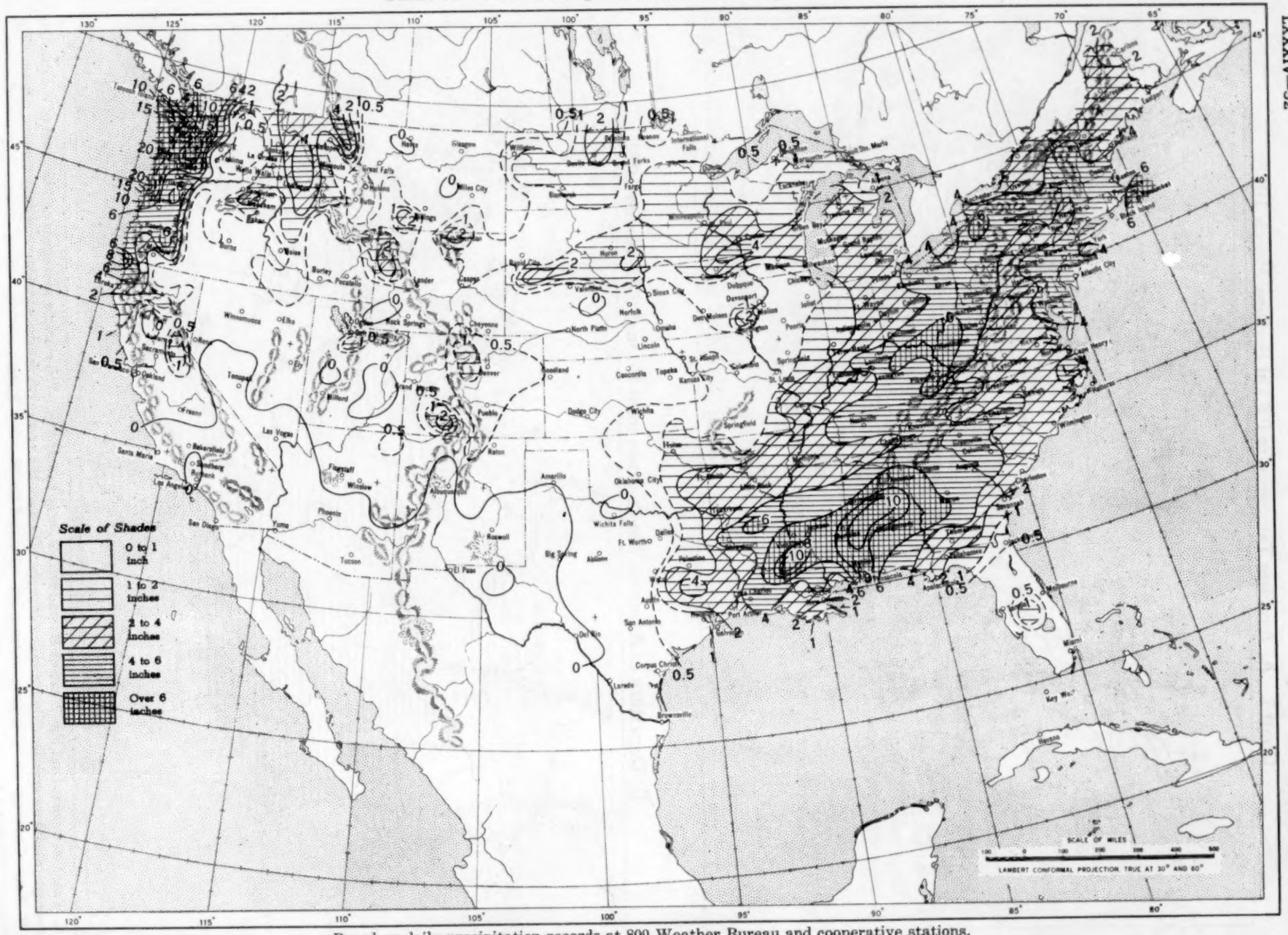


B. Departure of Average Temperature from Normal (°F.), March 1956.



A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

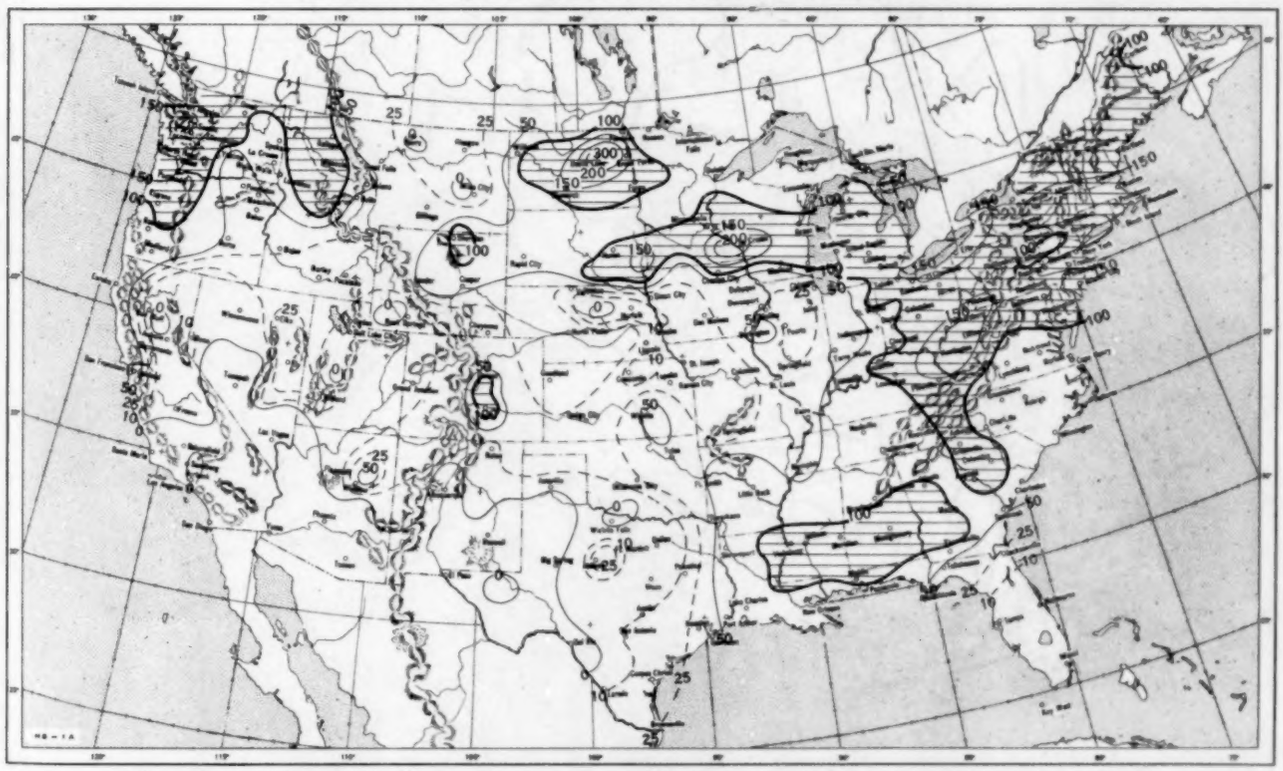
Chart II. Total Precipitation (Inches), March 1956.


Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

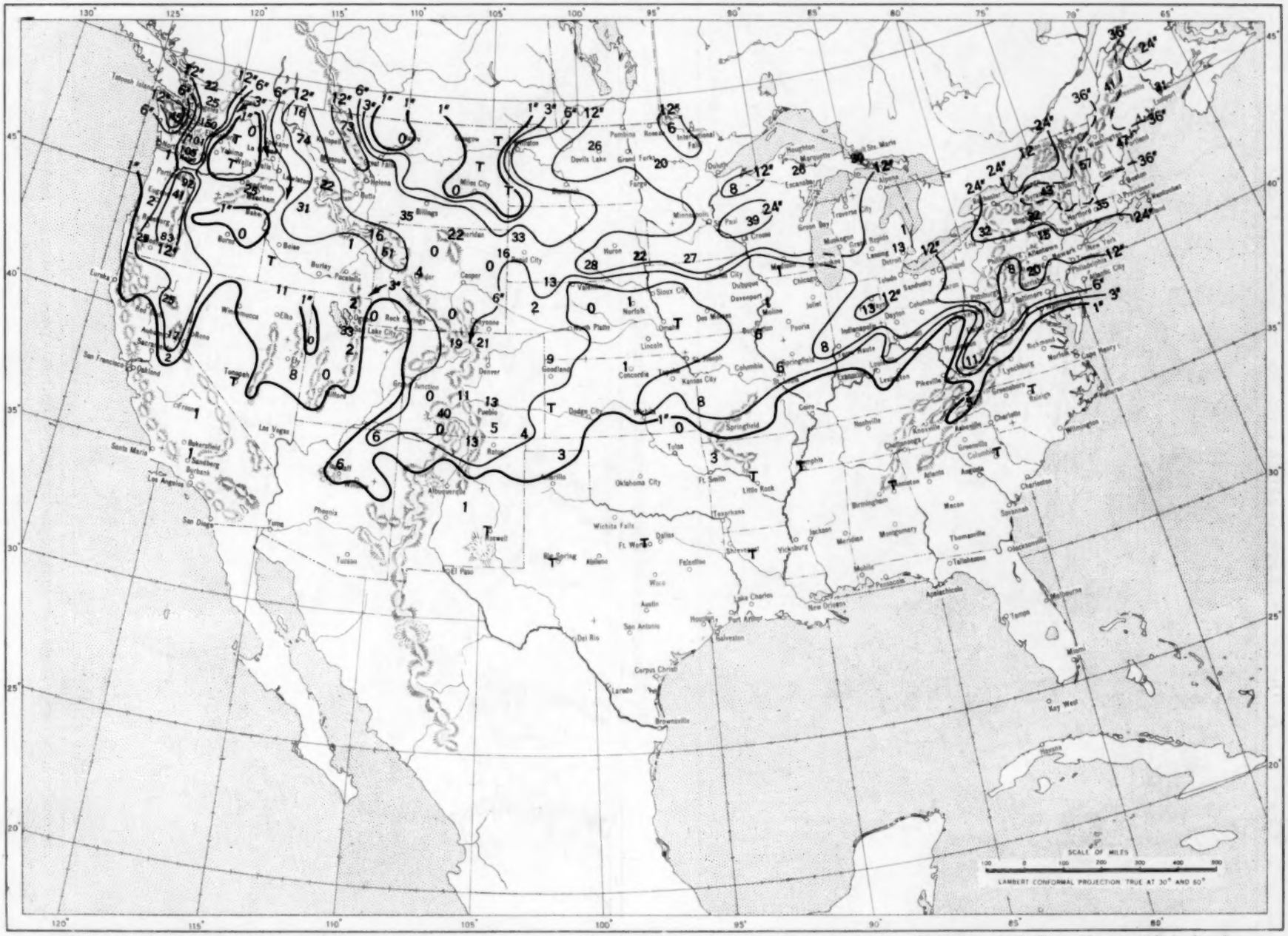
Chart III. A. Departure of Precipitation from Normal (Inches), March 1956.

B. Percentage of Normal Precipitation, March 1956.



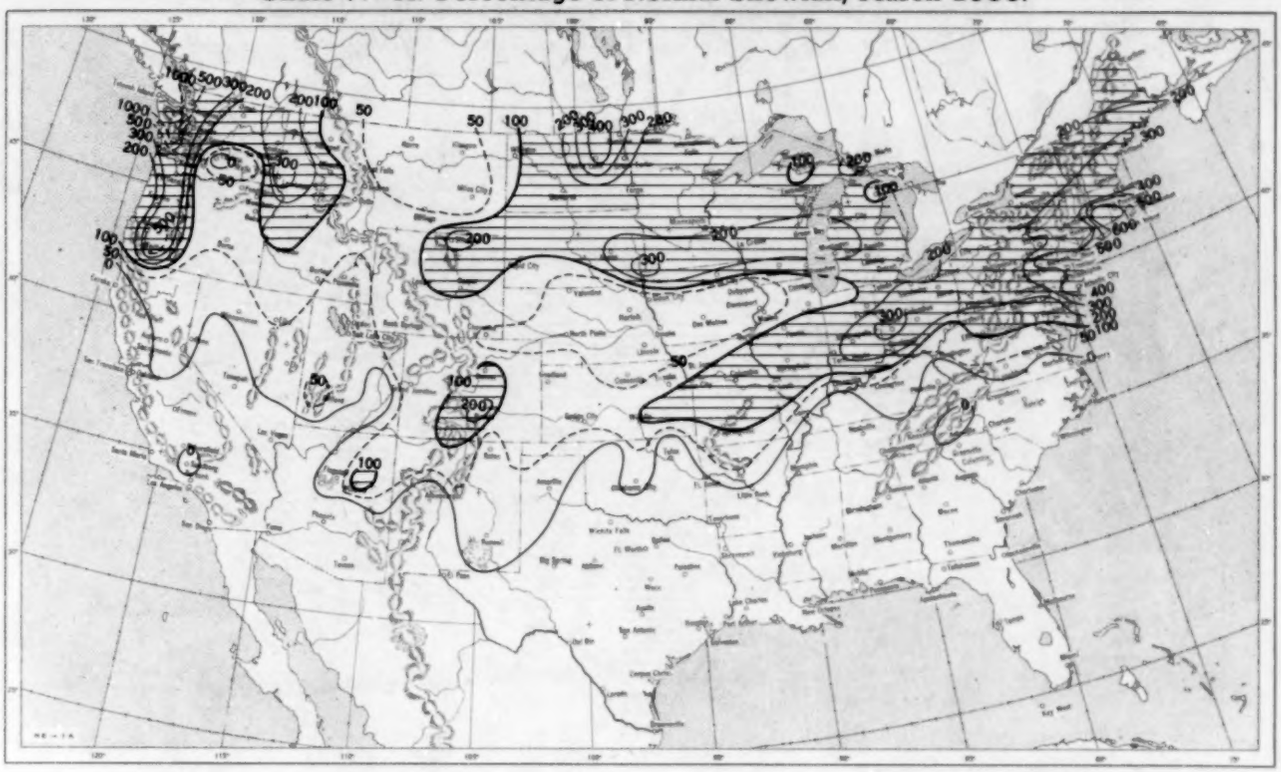
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), March 1956.

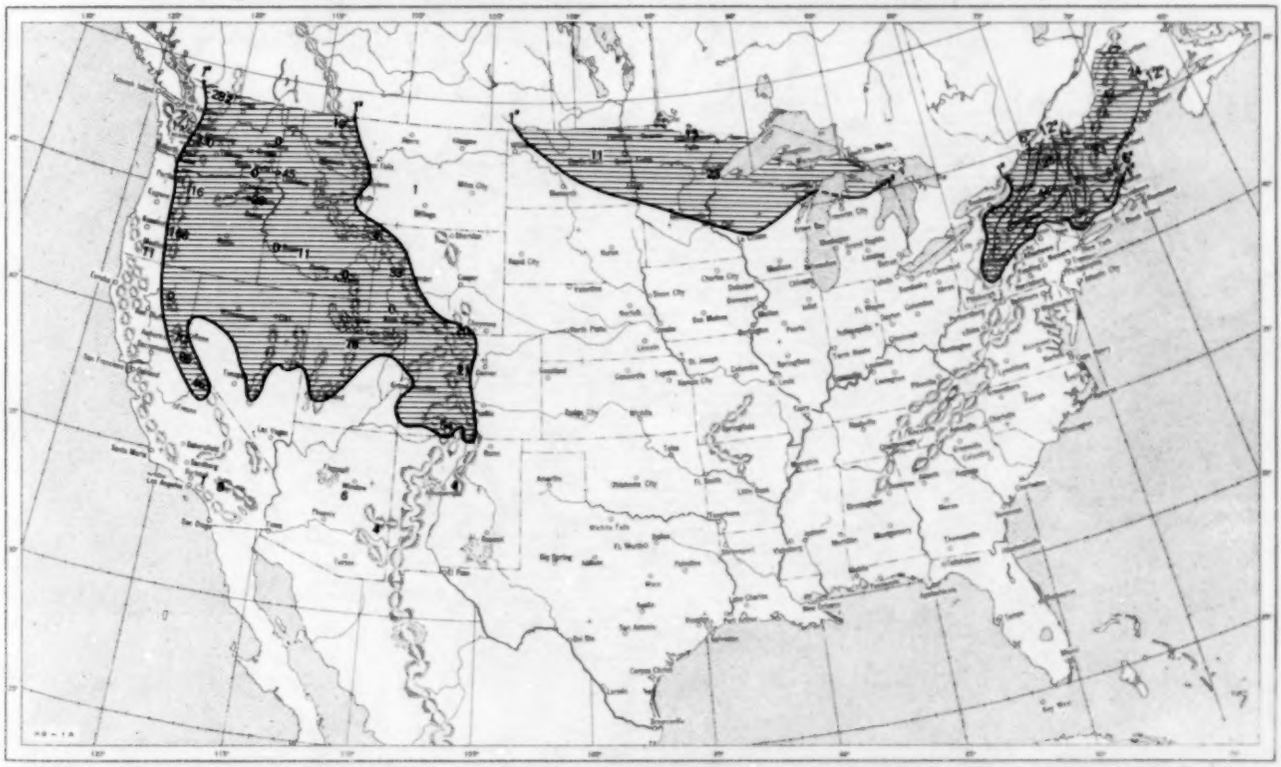


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, March 1956.

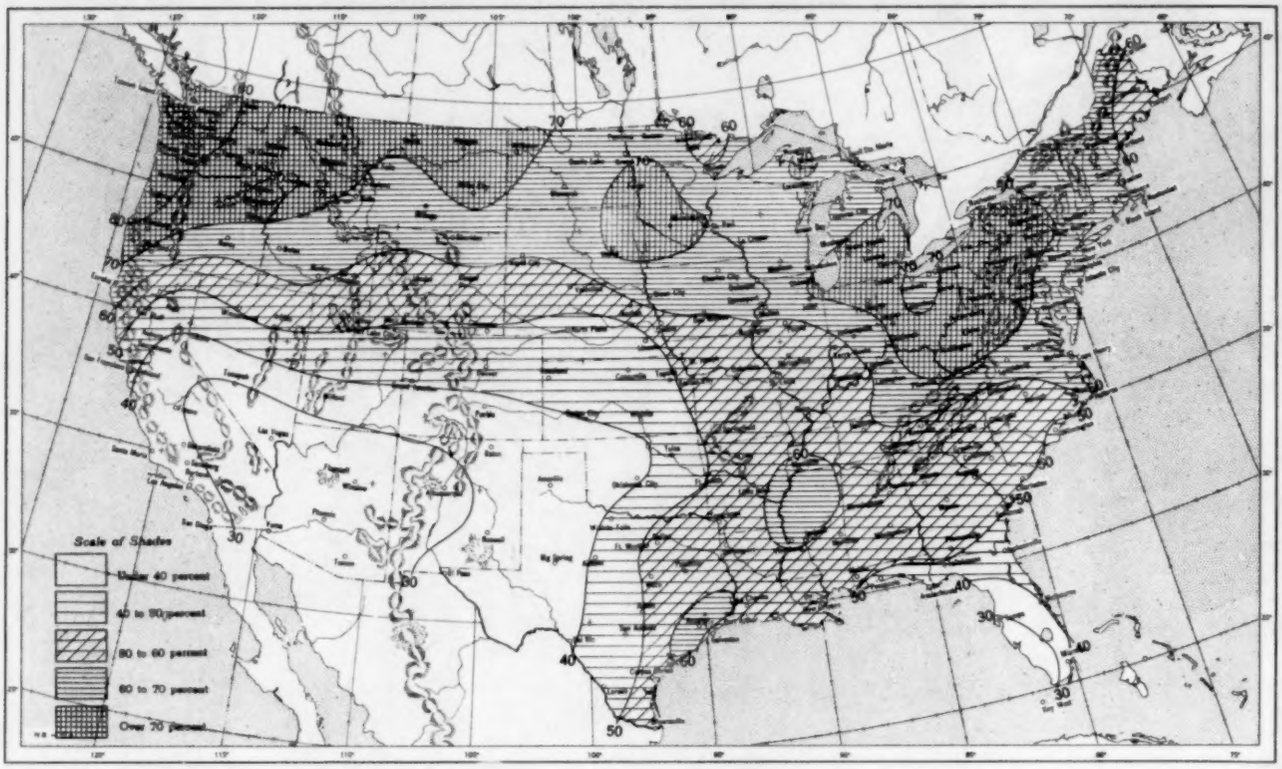


B. Depth of Snow on Ground (Inches). 7:30 a. m. E. S. T., March 26, 1956.

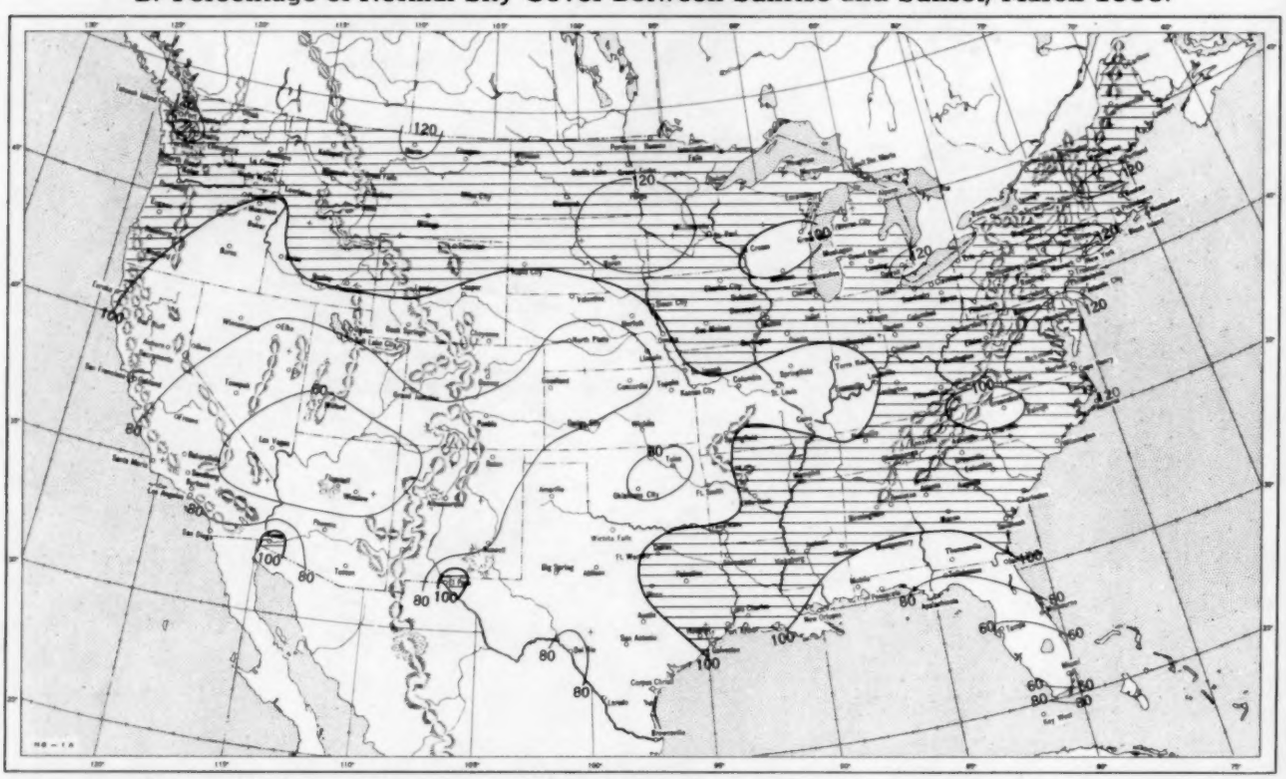


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, March 1956.

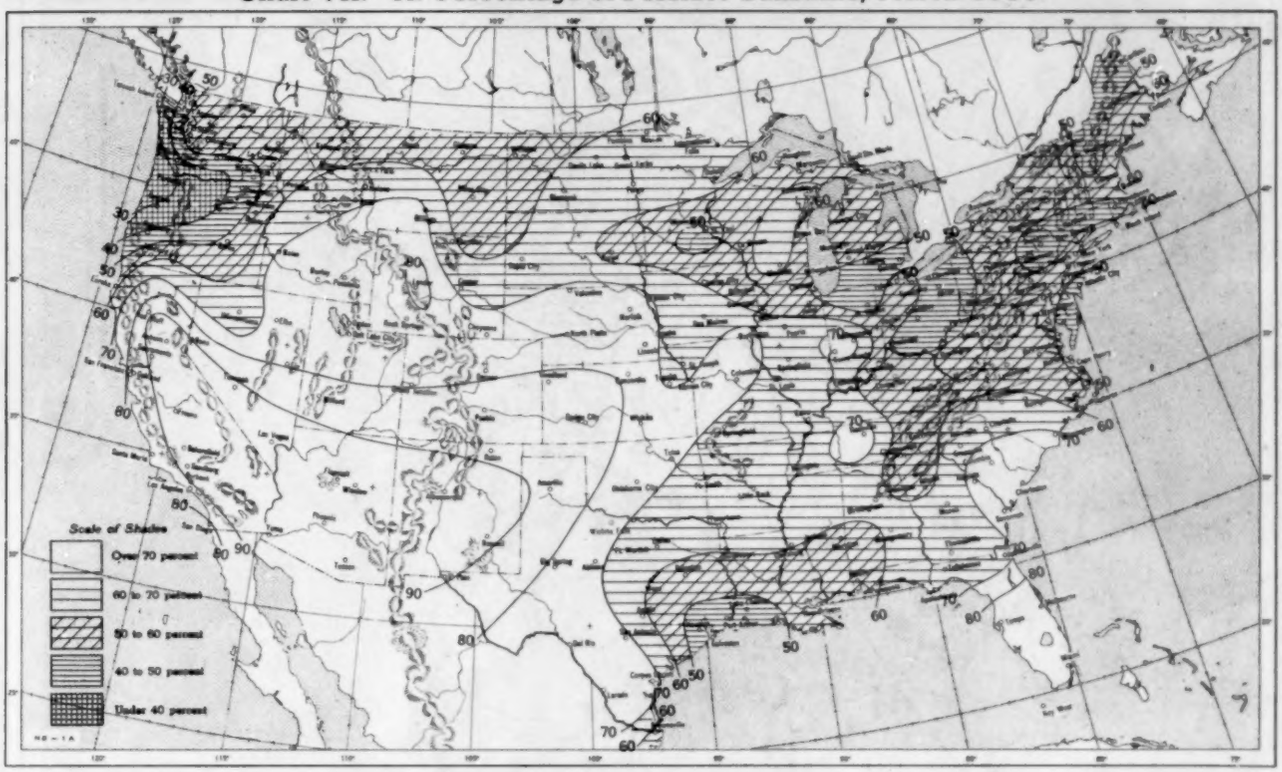


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, March 1956.

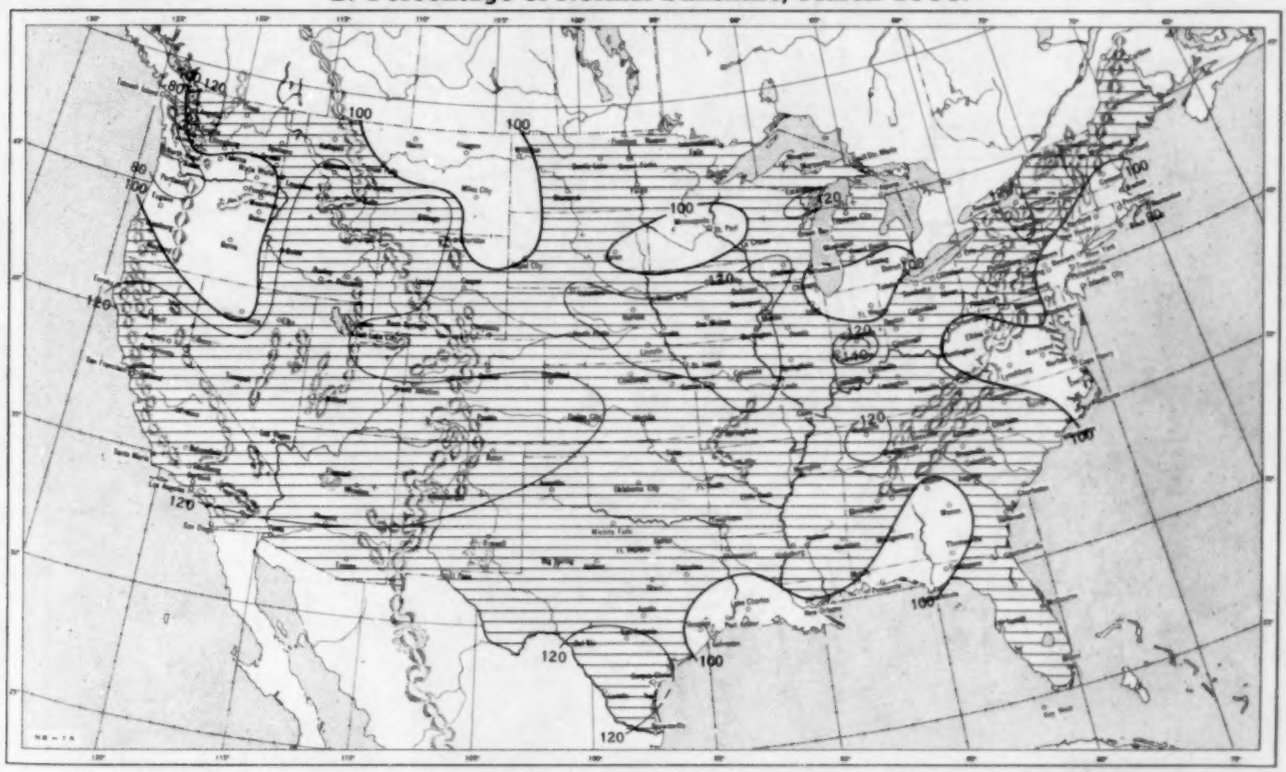


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, March 1956.



B. Percentage of Normal Sunshine, March 1956.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, March 1956. Inset: Percentage of Mean Daily Solar Radiation, March 1956. (Mean based on period 1951-55.)

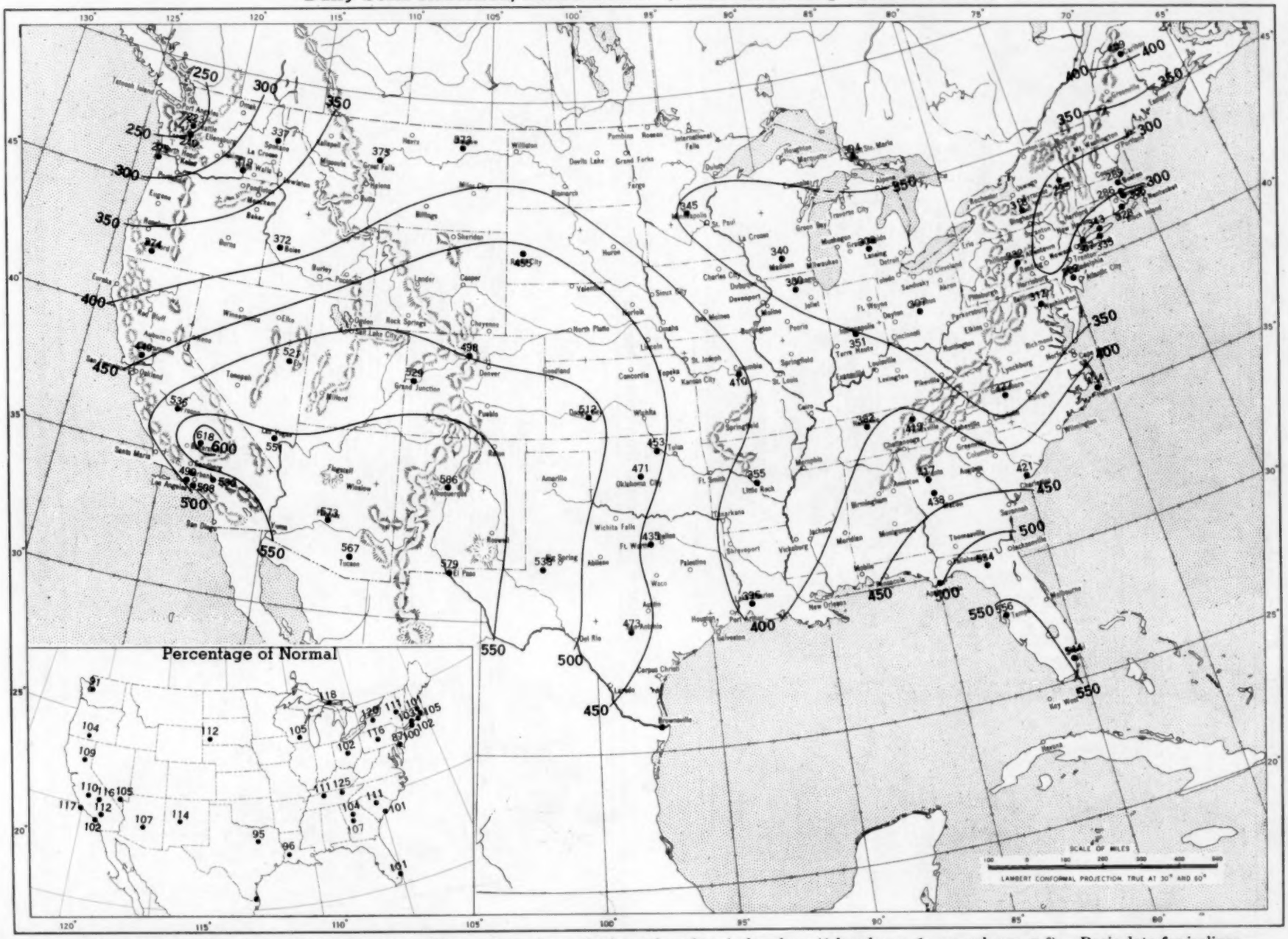
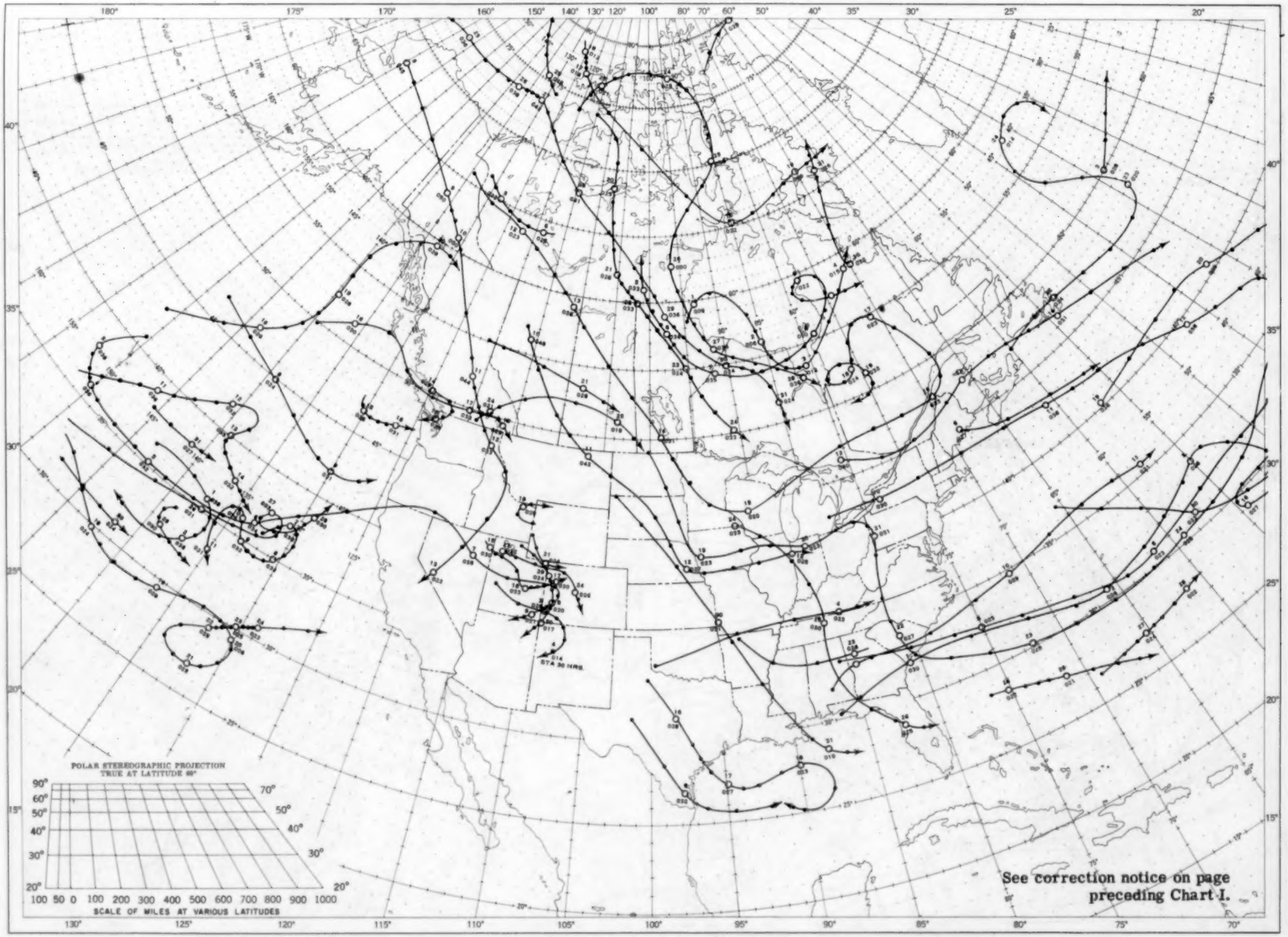


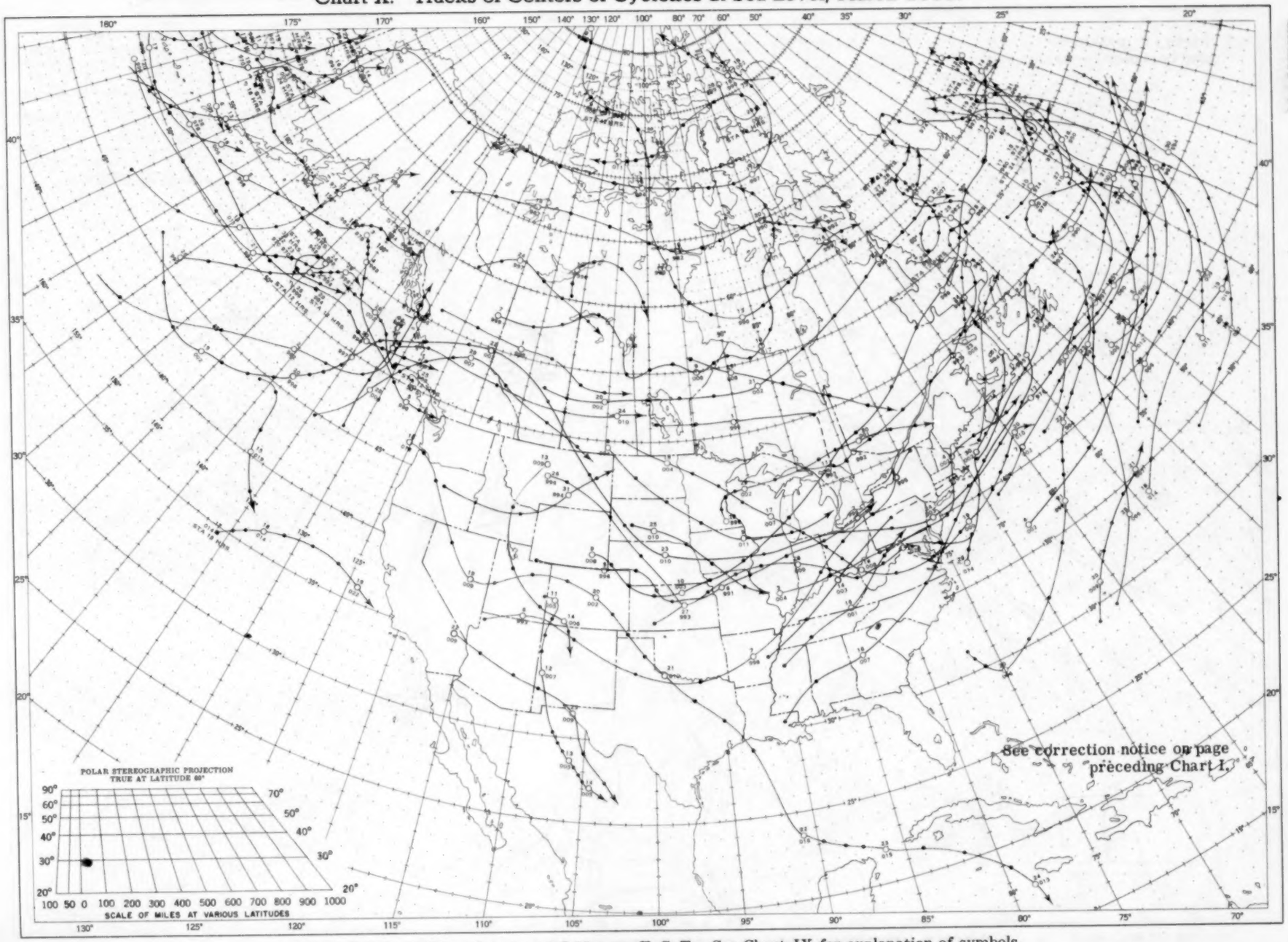
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, March 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000
See correction notice on page preceding Chart I.

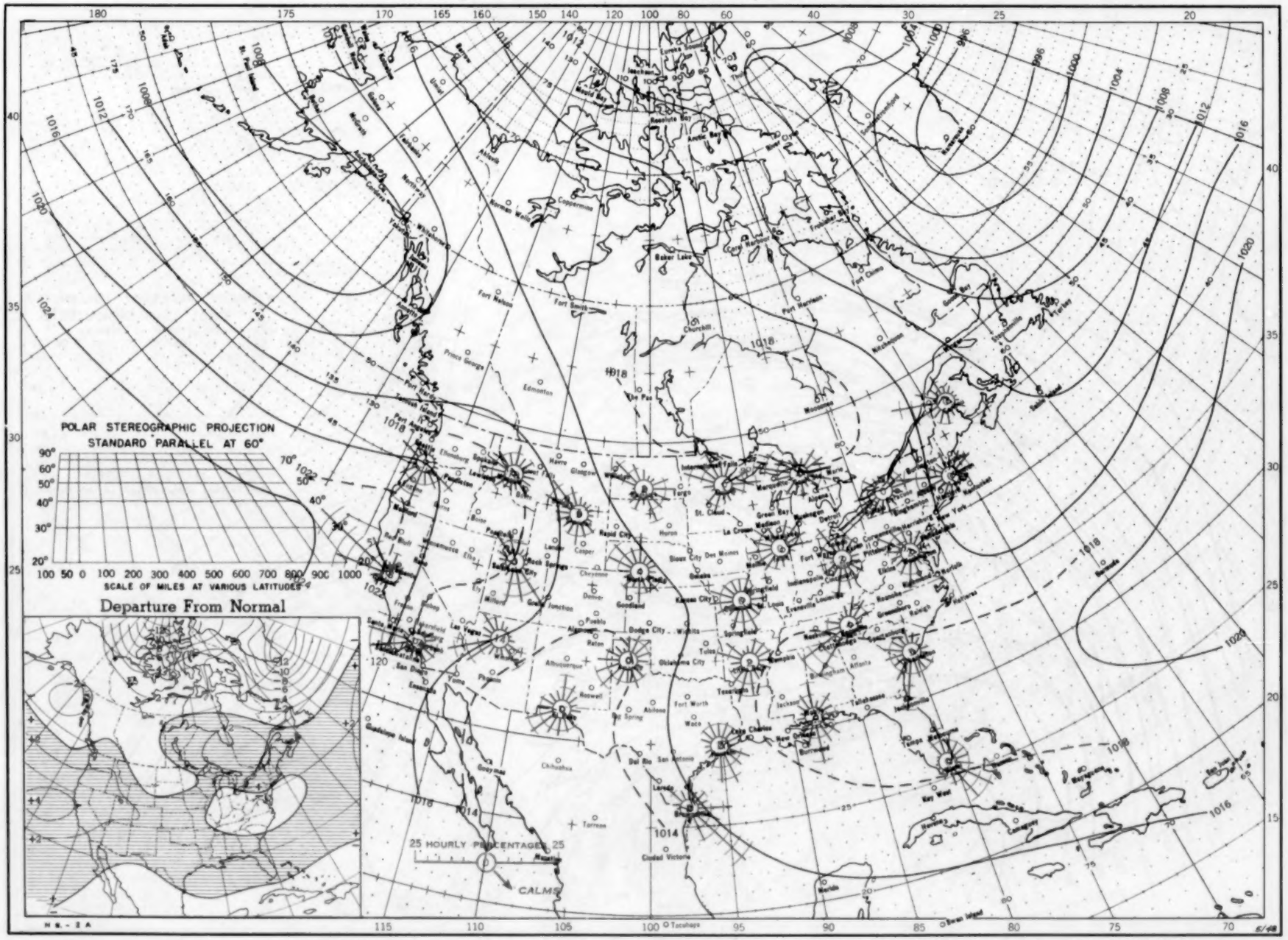
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, March 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
SCALE OF MILES AT VARIOUS LATITUDES
See correction notice on page preceding Chart I.

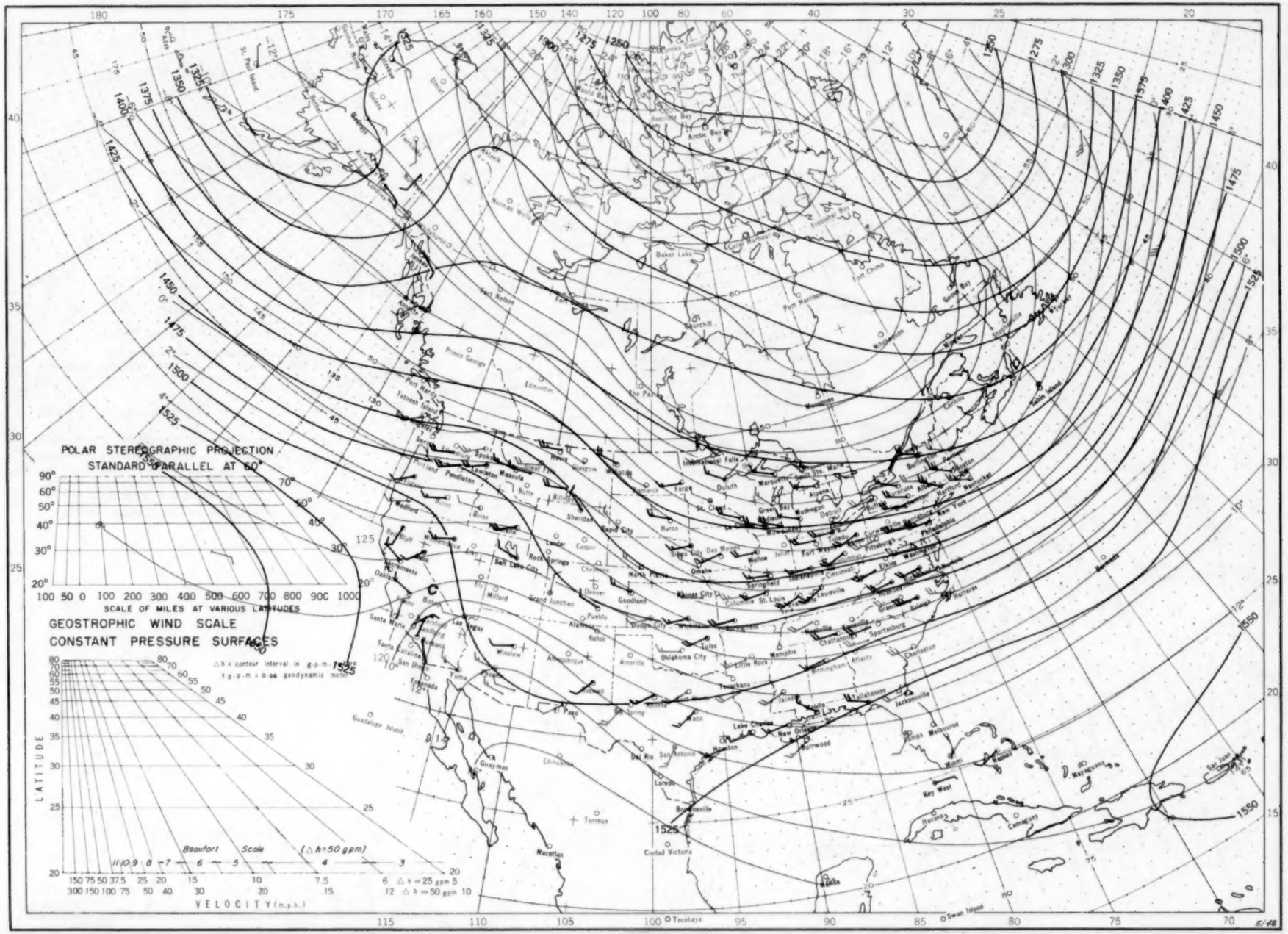
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, March 1956. Inset: Departure of Average Pressure (mb.) from Normal, March 1956.



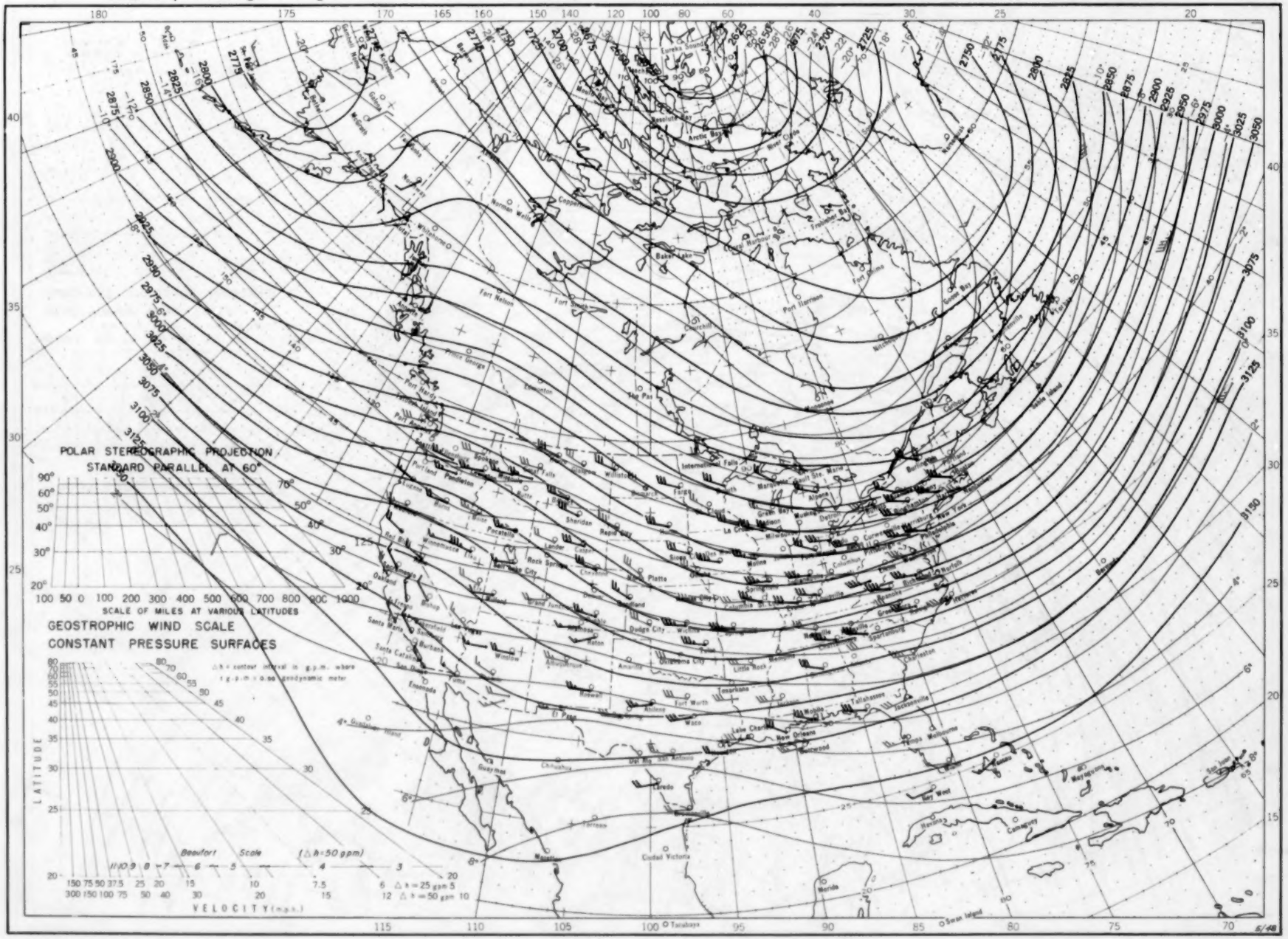
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), March 1956.



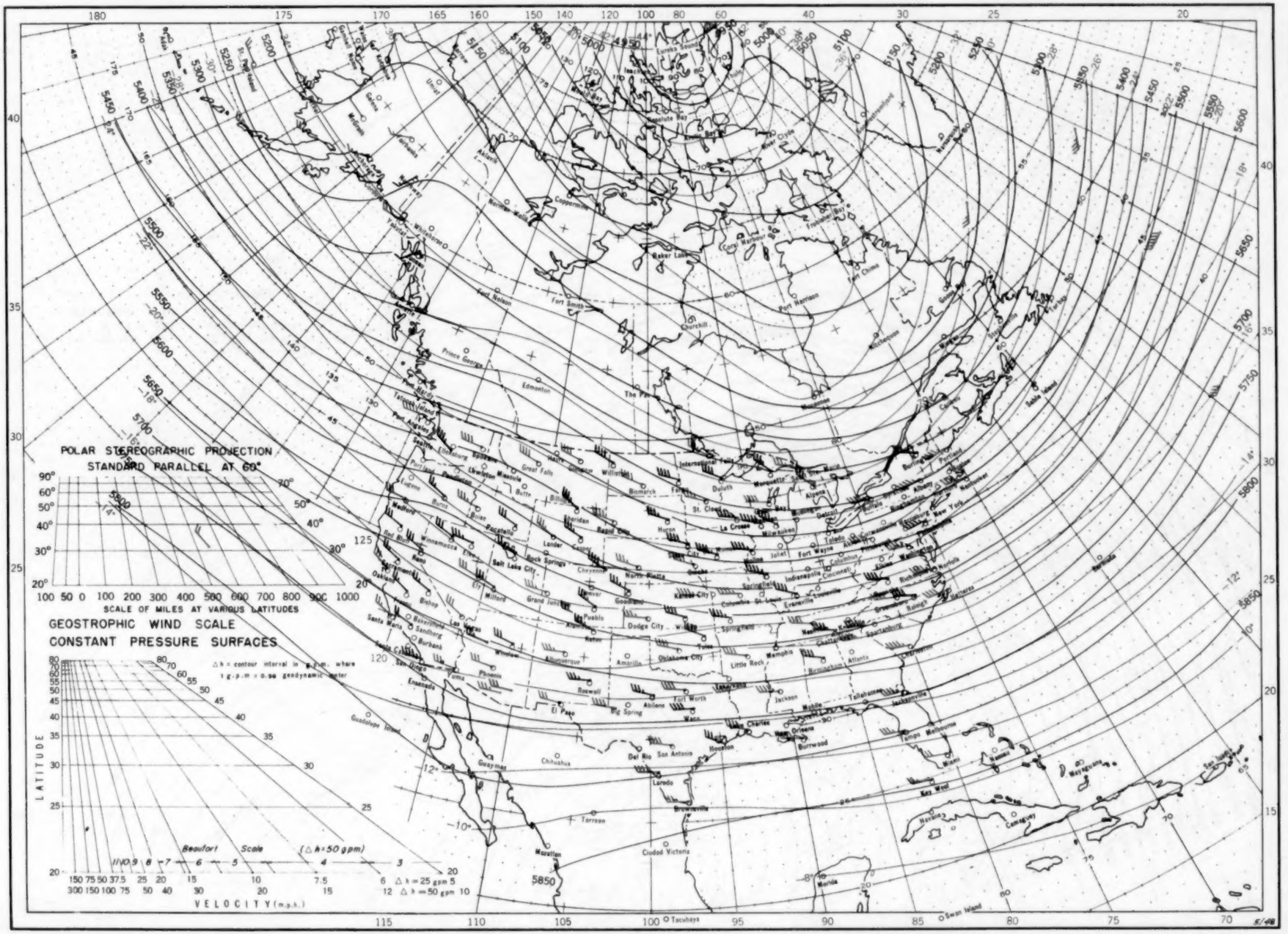
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), March 1956.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
GEOSTROPHIC WIND SCALE
CONSTANT PRESSURE SURFACES
LATITUDE
VELOCITY (m.p.h.)
Beaufort Scale
Δh = contour interval in g.p.m. where 1 g.p.m. = 0.98 geodynamic meter

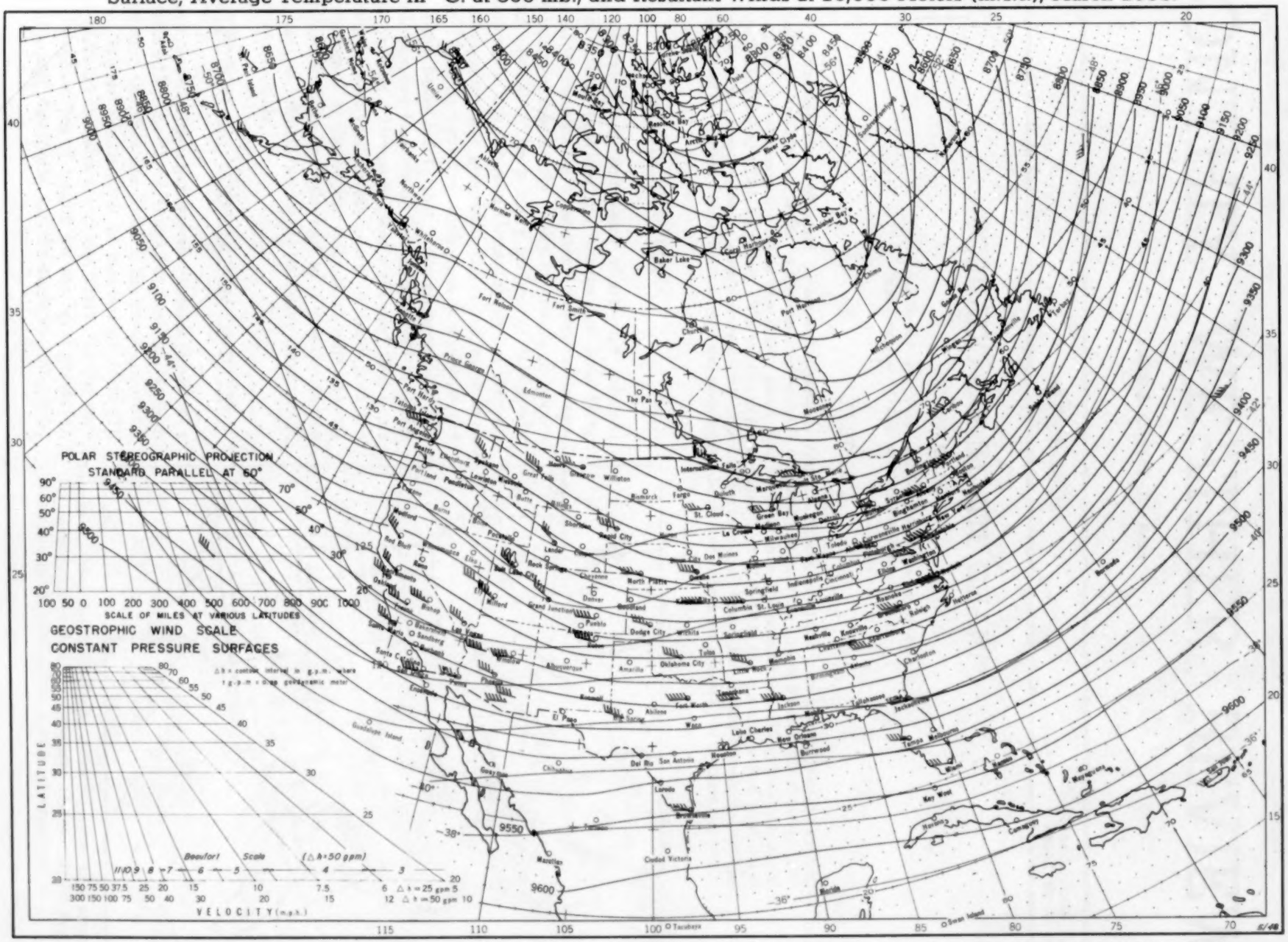
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), March 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), March 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.